TRN's

Making the Future Report

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

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Alternative Computer Chips: Post-Silicon Circuits

Executive Summary

Because it takes time to develop new computer chip technologies and retool the industry accordingly, there is an urgency to planning what comes next.

There are four basic directions: extending existing technologies, using spintronics to build faster transistors, building logic circuits using nanotechnology, and developing radically different technologies.

The challenges to continuing to shrink transistors using existing technologies include figuring out ways to etch smaller features into silicon and dealing with the laws of physics, which act differently in the realm of the very small. Existing technologies are probably viable for another decade.

Using spin rather than charge to carry out computations would require far less electricity, and would enable computers to do away with magnetic disk drives. Practical simple prototype devices could be made within five years.

Three broad areas of nanotechnology apply to computer chips: semiconductor nanowires, carbon nanotubes and molecular electronics. These nanoscale structures are formed by self-assembly. Nanotubes and nanowires could be used in simple devices within five years, and as alternative transistors in computers in 10 to 20 years.

Cellular automata technologies, which use large arrays of identical components, or cells, that affect each other in simple ways, have the potential to be faster and use less power than transistor-based logic.

Neural networks have many millions of switches that are interconnected like neurons, and so have the capacity to learn.

Electron wave computers, which use the wave interference patterns of electrons rather than current to represent the ones and zeros of computing, have the potential to be very small and very fast at solving certain problems.

Making practical computers from cellular automata, artificial neural networks, or electron waves means reinventing the computer from the ground up, including software and manufacturing processes. It will be at least one decade and perhaps two before any of these alternative architectures can be used to build practical computers.

What to Look For

Nano Circuits:

- Production nanotube or nanowire transistors
- Bulk nanotube or nanowire transistors
- Full processor made from nano transistors

Molecular Devices:

- Single-molecule transistor with nanowire electrodes
- Single-molecule transistors made in bulk
- Full transistor made from a single molecule
- All-molecular logic circuits

Spintronics:

- Spintronic logic circuits
- Full spintronic processor

Alternative Architectures:

- Quantum dot or molecular cellular automata logic
- Full processor made from cellular automata
- Electron wave logic circuits
- Nanowire or molecular artificial neural network

Shrinking transistors

The steady increase in computer speed—which affects everything from communications to car components to the stock market—is made possible by a steady decrease in the size of the transistors that make up the logic circuits of computer chips.

Smaller transistors mean electrical signals have shorter distances to travel, and so arrive more quickly. The practice of shrinking transistors to speed signals has worked well for the past 30 years, and it looks like existing technologies will be able to produce faster transistors for at least five years.

Look a little further into the future, however, and most possibilities call for much different manufacturing processes. Retooling an entire industry is no small task, and involves expensive bets on technologies that may or may not become future standards.

No one is saying that today's chips will be toast tomorrow, but the time it takes to develop new technologies and retool the industry means there is an urgency to figuring out what comes next.

This report will outline the major possibilities. There are four basic directions:

- Extending existing technologies by continuing to shrink transistors or by using other methods to speed transistors
- Tapping the attributes of particles like electrons to build spintronics transistors
- Building circuits from the bottom up using components at the molecular scale, including nanowires, carbon nanotubes and single molecules
- Developing radically different logic circuits from cellular automata, neural computing or electron waves interference technologies

Keeping the juggernaut rolling

Some researchers are looking to extend existing technologies further than may at first seem possible. The industry has already defied several rounds of premature predictions of its demise.

The first computer chips were built more than 40 years ago to replace individual transistors, which had, in turn, replaced vacuum tubes. For the past four decades improvements in silicon chips have generally followed the pattern Intel co-founder Gordon Moore observed in 1965 — the number of transistors on a computer chip, and its speed, doubles every 18 months.

The transistors commonly found on computer chips shunt electricity from a source electrode through the main channel of a transistor to a drain electrode. A gate electrode uses an electric field to turn the transistor on by allowing electricity to flow. (See How It Works, this page).

Today's transistor channels measure about 100 nanometers, which is 50 times smaller than the diameter of a red blood cell, but still about 1,000 times larger than an atom.

The challenges to continuing to shrink transistors using existing technology include being able to etch smaller features into silicon, and dealing with the laws of physics, which act differently in the realm of the very small.

The limits of light

Today's computer chips are made via photolithography processes that use chemicals and beams of light to etch transistors from semiconductor materials like silicon, and metal. The problem with continuing to make smaller circuits this way is light can only be focused through a lens or channeled by mirrors into an etching beam that spans about half the light's wavelength. Manufacturers have

How It Works

Simple switches

The transistors that form the electrical circuits that make up the logic gates of computer chips are relatively simple switches. They are field effect transistors, meaning they can be turned on and off using an electric field. A transistor includes a channel that runs from one end of the device to the other, a source electrode at one end, a drain electrode at the opposite end and a gate electrode that spans the channel.

When electricity flows through the gate electrode, it bathes the channel in an electric field, which makes the channel less resistant to the flow of electricity, and and causes electricity to flow from the source electrode to the drain electrode. A transistor is on when electricity is flowing through the channel.

There are about 55 million transistors on Intel's Pentium 4 chip, which is about the size of a thumbnail. The transistor channels on a Pentium 4 chip are about 60 nanometers long. A nanometer is one millionth of a millimeter, or the length of a line of ten hydrogen atoms.

Logic gates

A transistor that is on provides an input of 1, and a transistor that is off provides an input of 0. The output of one transistor can flow through the gate electrode of another. Combinations of transistors connected this way form logic gates, or logic circuits, that perform the basic binary logic operations of computing. Logic gates take in one or more binary inputs, or signals from transistors, and output a single signal, or answer.

The three basic logic circuits are AND, OR and NOT. An AND gate outputs a 1 only if all the inputs are 1, and returns a 0 if one or more of the inputs are 0. An OR gate returns a 1 if any of the inputs is a 1, and a 0 only if all of the inputs are 0. A NOT gate receives a single input, and returns the opposite of that input.

These three basic logic circuits can be combined to make more complicated logic elements, for instance a NAND, or NOT plus AND, gate. Circuits range in size from a simple NOT gate to large-scale circuits that use a million or more transistors each, and can also contain components like capacitors, which briefly store electrical charges, and multiplexors, which split single inputs into multiple outputs.

The smaller the transistor channel, and the shorter the wires between transistors, the faster an operation can be carried out, simply because it takes less time for electrical signals to travel shorter distances.

Today's models of the Pentium 4 chip are as fast as 3 gigahertz, which means they can carry out as adapted by using shorter wavelengths, but they can follow this strategy only so far before they reach the wavelengths of x-rays, which are extremely difficult to focus because they pass through lenses and mirrors unaffected.

Chip makers use ultraviolet wavelengths of 248 and 193 nanometers, which produce features as small as 130 nanometers. The next step for lithography is extreme ultraviolet, which has a wavelength of 13.5 nanometers. Extreme ultraviolet lithography requires mirrors rather than lenses, because such short wavelength light passes through lenses without being affected. Extreme ultraviolet lithography will be able to produce features as small as 45 nanometers. The challenge is producing convex and concave mirrors with nearly perfectly smooth surfaces. Extreme ultraviolet lithography could be in use in two to four years.

It is already possible to etch features as small as a few nanometers using electron beams and ion beams, but these processes are too expensive for mass production.

There's also the possibility of manufacturing traditional circuits without using photolithography. This involves new manufacturing processes, however. One promising possibility involves a very old technology—stamping. Researchers from Princeton University have found a way to stamp circuits onto silicon wafers using a quartz mold and microscopically thin layers of silicon melted by a laser. The process is relatively quick—it takes less than one millionth of a second to stamp a form—and can be used to create surface structures smaller than 10 nanometers because electron or ion beam lithography can be used to make the master stamps.

The stamping process could be used to manufacture circuits in about five years.

Approaching the quantum zone

The laws of quantum physics will pose a major challenge around the 50-nanometer mark. In transistor channels of that size, electrons are harder to control. Particles, including electrons, also behave like waves, and waves, including light, also behave like particles; this dual nature of matter produces significant effects at very small scales.

An electron's wave nature is described by its wave function, a mathematical map that defines where in a cloud-like region an electron can exist. Probabilities determine where in the wave function the electron is likely to be found in its particle incarnation. If an electron's wave function overlaps a barrier that, according to classical physics, is insurmountable to the electron, the electron has some small probability of popping up on the other side. The smaller the barrier, the greater the probability. This means that the smaller a transistor is, the more electrons will tunnel through the channel when it is turned off.

Researchers from the University of California at Berkeley have fabricated double-gate transistors—essentially transistors with stronger barriers—that block the flow of electrons in channels as short as 15 nanometers, and their calculations show that the design will work in channels as short as 10 nanometers. Current manufacturing processes would have to be changed to form a gate many as 3 billion logic operations per second. This makes them around 100 times faster than computers sold a decade ago.

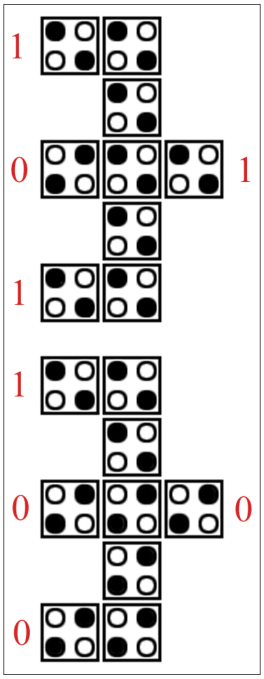
Spin

Theoretically, transistors could use magnetic fields rather than electric fields to switch on and off. In addition to electric charge, electrons have magnetic orientations — spin up and spin down — that are analogous to the opposite poles of a kitchen magnet. There are ordinarily roughly equal numbers of spin up and spin down electrons in a current of electricity.

Ferromagnetic materials can be used to sort out the two spins, and a current of electrons that spin in just one direction can be blocked by a magnetic field. This mechanism can be used to switch current in a transistor.

Self-sufficient cells

Cellular automata dispense with wires in favor of simple, repeated components, or cells, that can pass signals along to neighboring cells.



In one proposed arrangement, a cell consists of four islands capable of holding a single electron each. When a cell contains two electrons, they repel each other and move to opposite corners. Electrons in the top left and bottom right corners could represent 1, and electrons in the top right and bottom left corners 0.

Because electrons repel each other, adjacent cells adopt the same configuration. Flipping the positions of the electrons in one cell causes the electrons in a neighboring cell to change positions, and so on down a line of cells.

If a cell is adjacent to three or four other cells, it can only be flipped by changes to a majority of the adjacent cells. The basic binary logic gates — AND, OR and NOT — can be configured from arrangements of these majority gates. (See diagram)

Brain mimics

Neural chips create brain-like neural networks, which are usually implemented in software. Networks of neurons are heavily interconnected and the firing electrode on the bottom of a transistor in addition to the one on top. (See Tinier Transistors Keep Moore's Law on Track, page 10)

This could be done in five to seven years.

Heating up

Another challenge has been uncovered by Texas A&M researcher Laszlo Kish, whose calculations show that circuit sizes of about 40 nanometers could produce unsolvable heat problems. Smaller circuits require smaller voltages, and these weaker signals are more vulnerable to errors caused by interference from the energy generated by heat. (See Heat' s onto Silicon, page 9)

Shrinking circuits from 100 to 40 nanometers will increase thermal noise by about a factor of three, which is enough to cause an intolerable number of errors, according to Kish's calculations. Following Moore's Law, the industry will reach the 40-nanometer circuit size mark at about the end of the decade.

Even short of disrupting chips' logic, heat is a big problem. The faster chips become, the more heat they produce, and dissipating heat takes power. This is especially troublesome for devices that run on batteries.

A possible solution is reversible logic. The idea is to reset bits by reversing a logic operation. If, for instance, a reversible logic chip calculates that one plus one is two, it would then subtract one from two to get back to where it started. The idea is to avoid needlessly erasing bits. Erasing a bit means draining the electric charge from a transistor's gate electrode, which produces heat. Theoretically, nearly all of the energy wasted through heat could be conserved by recycling the electricity to reverse logic.

Reversible logic has been kicking around the research community for years. Although the principle is sound, it is too soon to tell whether there are any practical advantages to building chips that include reversible logic.

Reconfigurable chips and evolution

There are also ways to improve computer chips that don't involve speeding them up. One possibility is making chips reconfigurable so that they can be optimized for specific tasks and then changed again to better handle other tasks. Reconfigurable computing is a decades-old idea that is becoming more realistic with the greater densities and lower costs of field-programmable gate arrays (FPGA), the building blocks of changeable circuits.

Field-programmable gate array chips contain thousands of transistors that can be rewired in the field to form different logic circuits. They are used increasingly for application-specific integrated circuits (ASICs), the chips that offload from the central processor functions like rendering graphics and handling network protocols. Many field-programmable gate arrays can only be programmed once, but chips that are dynamically reconfigurable have been developed. Someday software could determine the structure of the chip it runs on.

Dynamically reconfigurable chips set the stage for chips that adapt to changes in their environment, and even chips that evolve. of one neuron can trigger another. Stimuli such as sensory data or a piece of software causes sequences of neurons to fire, and over time the network learns by having the same sequence of neurons fire in response to the same stimulus.

Unlike ordinary logic circuits, which have fixed links between components, connections between artificial neurons can vary in strength, which is what makes it possible for the network to learn over time. The more recently one neuron has triggered another, the stronger the connection between the two and the easier it is for the first neuron to trigger the second again.

Possible neural hardware architectures include field programmable gate arrays, whose logic can be programmed after the chip is made; Josephson junctions, which are a type of superconducting circuit; and random networks of huge numbers of carbon nanotubes or semiconductor nanowires.

Who to Watch

Nano Circuits:

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Researchers are developing evolvable hardware that combines field-programmable gate arrays with genetic algorithms. In these systems, chip configurations that handle a particular task well are more fit and therefore advance to the next generation. The algorithm generates thousands of generations of chip designs and in the process introduces random mutations. Genetic algorithms have proved to be very efficient at finding optimal configurations.

Architecture:

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Nitin Samarth, Pennsylvania State University
University Park, Pennsylvania
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Spin

Today's circuits control the flow of electrons by inducing or blocking electric charge. Electrons also have spin, a magnetic property similar to the two poles of a refrigerator magnet. Using spin rather than charge to carry out computations would require far less electricity, and would enable computers to do away with magnetic disk drives, because the spin states of electrons remain stable even when the power goes off. The trick is being able to control spin and switch it quickly.

Many researchers are working on controlling spin in order to use it to produce power-efficient, cheap computers. Researchers from Durham University in England, for instance, have constructed a circuit that carries out a logic operation by moving a magnetic wall along a wire that contains a series of hairpin turns. In this device, the electrons are stationary and the region where the electrons' spins flip moves along the wire like a wave in a narrow canal. (See Bent Wires Make Cheap Circuits, page 27)

A potential building block of spin-based computers is the spin transistor, which uses a magnetic field to block spin-polarized current from flowing through the device rather than an electric field to induce a current of charge. So far it has proved difficult to preserve the spins of electrons as they travel through a transistor's channel. It is also difficult to preserve electrons' spins as they pass from one type of material to another, which is what happens as current flows through a transistor.

Physicists from the universities of Iowa and Missouri have proposed a type of reconfigurable spin transistor. Rather than producing a magnetic field using the equivalent of a fixed gate electrode, the device would produce magnetized regions on-the-fly. The large potential advantage of this device is that reconfiguring a computer chip would be as easy as writing information to a magnetic disk. (See Magnetic Transistor Means Changeable Chips, page 29)

Practical simple prototype devices that use spin rather than electrical charge to compute could be made within five years.

Longer-term, researchers are looking to use the phenomenon in quantum computers, which use the attributes of particles like atoms or electrons to compute, and are theoretically many orders of magnitude faster than classical computers. Practical quantum computers, which are theoretically fast enough to render all of today's security software useless, are at least 20 years away.

Race to the bottom

All of the approaches to chipmaking mentioned so far involve the same basic manufacturing process: etching circuits using lithography. This top-down approach requires sophisticated machines that impose order on ever smaller scales. A potentially much simpler and cheaper way to go is to use the forces of nature to induce order from the bottom up.

There are three main areas of nanotechnology that apply to computer chips:

- Semiconductor nanowires
- Carbon nanotubes
- Molecular electronics

These nanoscale structures are formed by atoms and molecules assembling themselves into patterns according to their chemical properties and the laws of physics. So far, no one has produced entire computer chips or even complete transistors using these techniques alone. But the possibility exists, and in the meantime nanodevices could be combined with traditional chipmaking techniques in a hybrid approach.

Ultimately, nanotechnology and bottom-up chipmaking represent not only hope for keeping computer chips developing apace but also a more realistic route to the vision of dirt cheap chips built into everyday items.

Raining atoms

Nanowires are tiny structures made from materials that have well-known electrical properties and that are compatible with chip manufacturing processes.

The tiny wires, which can be narrower than one nanometer in diameter, are most likely to be the first nanotechnology to gain a foothold in chip manufacturing. Researchers have found ways to produce segmented nanowires of different materials, and nanowires of a core material surrounded by different layers. Harvard researchers have made a nanowire transistor by connecting source, drain and gate electrodes to different layers of a single, multilayer nanowire. (See Coax Goes Nano, page 16)

Given smaller nanowires, the technique could pack as many as a trillion transistors per square centimeter, some four orders of magnitude more than the 10 to 100 million transistors per square centimeter that existing photolithography techniques allow.

Smart soot

Carbon nanotubes are rolled-up sheets of carbon atoms that form naturally in soot. Like nanowires, they can be smaller than one nanometer in diameter.

Nanotubes are nearly ready-made transistors. In 1998, a group of researchers from the Netherlands made a transistor from a nanotube 1 nanometer in diameter by simply laying the nanotube across two electrodes. The resulting channel as about 100 times smaller than that of a standard silicon transistor.

Since then many research teams have made similar devices that use a carbon nanotube as the semiconducting channel. Last year two research teams separately showed that transistors made with single-nanotube channels outperform ordinary transistors.

Several groups of researchers have formed primitive logic circuits from nanotubes. The Dutch team made circuits with as many as three nanotube transistors, including an inverter, or NOT gate, a NOR gate, and a memory cell. IBM researchers made a NOT gate from a pair of transistors that shared a single nanotube. (See How It Works)

The long and short of molecules

And then there's the prospect of making computer chips, or at least chip components, in test tubes. Chemistry is about manipulating molecules, and nanotechnology, in some respects, is about focusing chemists' attention on using molecules themselves rather than their bulk properties. Molecular electronics could eventually be used in computer chips.

DNA has generated a lot of interest recently because the molecules can be extremely long and can be coaxed to self-assemble into complex structures. Researchers are exploring ways of using DNA as nanowires, as templates for forming nanowires of other materials, and as frameworks for containing and aligning metal and semiconductor nanoparticles.

Researchers are also working with increasingly complicated polymer molecules. In addition to making standard-size transistors out of plastic for flexible computer displays, researchers are using polymers in nanoelectronics. One research team has formed tightly packed arrays of polymer nanowires that have conducting cores and insulating outer layers. (See Chemists Brew Tiny Wires, page 25)

Making transistors from single molecules would provide the ultimate in miniaturization. Researchers are beginning to explore this possibility, and two teams have used single molecules as channels in prototype transistors. The devices perform poorly, however, and it's not clear how to wire molecular transistors together, making it unlikely that single-molecule transistors will be practical in the next 10 or even 20 years. (See Mixes Make Tiniest Transistors, page 27)

Watchmaker's nightmare

One trouble with making microscopic devices from ever smaller parts is getting everything to line up in the right places. Circuits require parts to be interconnected and closely spaced. Researchers have produced parallel and perpendicular arrays of nanotubes and nanowires, but so far wiring nanotube and nanowire transistors into circuits has required comparatively massive lithographically formed electrodes.

Harvard researchers have devised a way to form transistors from crossed nanowires, and used the technique to build a simple calculator prototype from nanowires that were 10 to 30 nanometers in diameter and several microns long. The technique involves depositing nanowires in fluid flowing in one direction, and then depositing another layer of nanowires in fluid flowing in the perpendicular direction. (See Crossed Nanowires Compute, page 13)

Stanford University researchers have devised a technique for growing carbon nanotubes between electrodes, which should significantly increase yields of nanoscale devices. Previously, researchers grew nanotubes first and then used lithography to form electrodes on top of them, a process that often damages the nanotubes. (See Nanotubes Grown in Place, page 23)

Nanotubes and nanowires could be used in simple devices within five years, and as alternative transistors in computers in 10 to 20 years.

Changing horses

Researchers are also exploring several radically different technologies that have the potential to carry out computations, including cellular automata, neural computing and electron waves. Making practical computers out of these technologies means reinventing the computer from the ground up, including software and manufacturing processes.

These technologies have significant potential advantages over today's silicon chips, however—each different from the others.

More than 50 years ago computer pioneer John Von Neumann worked out a way to compute that doesn't involve transistors or even wires, but instead uses large arrays of identical components, or cells, that affect each other in simple ways.

Each cell can be switched between two states that can represent the 1s and 0s of computing. The cells communicate via signals generated by chain reactions along lines of cells. (See How It Works)

Sans wires, these extremely tiny, identical components could be made very cheaply via self-assembly using nanotechnology techniques under development. Cellular automata also have the potential to be faster and use less power than transistor-based logic. Researchers are working out ways to add clock signals to cellular automata schemes or even carry out logic operations without a clock. Computer clocks send timing signals throughout a computer chip's circuits to synchronize logic operations. (See Quantum Dot Logic Advances, page 31)

Neural computing involves constructing artificial neural networks from electronics. Neural networks mimic biological brains, including the brain's capacity to learn. Finding ways of building neural networks in hardware could make them faster than software-only neural networks. Researchers are developing neural computers using field-programmable gate arrays; Josephson junctions, which are a type of superconducting circuit; and random networks of huge numbers of carbon nanotubes or semiconductor nanowires.

Neural computers are not likely to be used for general-purpose computing, but they could prove useful for controlling robots and other machines, and as special-purpose data analysis processors.

Electron wave computers use the wave interference patterns of electrons rather than current to represent the ones and zeros of computing. Researchers at the University of Missouri at Rolla have proposed an electron wave computer architecture that would use networks of microscopic wire rings as paths for electron waves to follow. (See Electron Waves Compute, page 33)

Electron wave computers have the potential to be very small. The method could also be used to make massively parallel processing devices, similar to quantum computers, that have the potential to solve certain problems faster than the fastest silicon computer because millions of potential answers could be examined at once rather than one at a time.

It will be at least one decade and perhaps two before any of these alternative architectures can be used to build practical computers.

Time and money

Given the central role of the microprocessor in industrialized societies and economies, there are plenty of resources and expertise being applied to the challenge of keeping the advance of computer technology on pace. Processes like extreme ultraviolet lithography should keep today's chip technology viable for another decade, if not longer. Alternative technologies, fueled in part by the nanotechnology boom, should mature in time to step in when silicon starts to fade.

There will also likely be a transition period when new technologies, particularly nanotubes and nanowires, are integrated into the chipmaking process. Nanotube and nanowire transistors could show up in computer chips within a decade.

Recent Key Developments

Advances in today's technology:

- A thermodynamics analysis spells trouble for today's chips (Heat's on Silicon, page 9)
- Studies show transistors have room to shrink (Tinier Transistors Keep Moore's Law Track, page 10)
- A stamp mold makes smaller chip features (Stamps Bang out Silicon Lines, page 11)
- Sapphire chips with speedy optical interconnects (Sapphire Chips Linked by Light, page 12)

Advances in nano logic:

- Logic circuits made from silicon nanowires (Crossed Nanowires Compute, page 13)
- Logic circuits made from carbon nanotubes (Tiny Tubes Make Logic Circuits, page 14)

Advances in nano devices:

- A high-performance nanotube transistor developed by Stanford, Cornell and Purdue Universities in November, 2002
- Layered semiconductor nanowires and a layered-nanowire transistor (Coax Goes Nano, page 16)
- Multiple-semiconductor nanowires (Tiny Wires Turn Chips Inside Out, page 17)
- A single-walled carbon nanotube transistor (Nanotube Kinks Control Current, page 19)
- A multiwalled carbon nanotube transistor (Jolts Yield Nanotube Transistors, page 20)
- A gold nanoparticle-carbon nanotube transistor (Spot of Gold Makes Tiny Transistor, page 22)

Advances in nano fabrication:

- A method for making the electrodes on the sides of nanotubes developed by the University of Cambridge and Hitachi Cambridge Laboratory in January, 2003
- A Y-branch nano transistor designed by the University of Würzburg in Germany in November, 2002
- A method for growing nanotubes between electrodes (Nanotubes Grown in Place, page 23)
- A method for growing nanotubes on specific sites (Nanotube Chips Draw Near, page 24)
- An array of vertical, electrically wired nanotubes (Nanotube Array Could Form Chips, page 24)

Advances in molecular devices:

- An array of insulated polymer nanowires (Chemists brew tiny wires, page 25)
- A metal-molecule-metal junction developed by Bell Labs in January, 2003
- Two single-molecule transistors (Mixes Make Tiniest Transistors, page 27)

Advances in spintronics:

- A magnetic logic circuit (Bent Wires Make Cheap Circuits, page 27)
- A design for a magnetic transistor (Magnetic Transistor Means Changeable Chips, page 29)

Advances in alternative approaches:

- A cellular automata logic scheme shows power gain (Logic Scheme Gains Power, page 30)
- A clock for a cellular automata logic scheme (Quantum Dot Logic Advances, page 31)
- A molecular cascade logic scheme developed by IBM Research in October, 2002
- A logic scheme based on electron waves (Electron Waves Compute, page 33)

Heat's on Silicon

By Kimberly Patch, Technology Research News
January 15/22, 2003

Moore's Law has been under attack of late, and probably for good reason.

In 1965 Intel co-founder Gordon Moore observed that the number of transistors in a silicon computer chip was doubling every year. What has become known as Moore's Law has held true—with an adjustment to 18 months rather than every year—for more than three decades.

A researcher from Texas A&M University has shown that the laws of physics are close to catching up with Moore's Law in a way not widely thought about. The culprit is heat, according to Laszlo Kish, an associate professor of electrical engineering at Texas A&M University.

More conventional predictions of Moore's Law's demise concentrate on the laws of physics that indicate the difficulty of etching increasingly smaller transistors into silicon. Today's circuits measure 100 nanometers, or about 50 times smaller than the diameter of a red blood cell. To keep pace with Moore's Law, circuit size will have to shrink to about 40 nanometers by the end of the decade.

According to Kish's calculations, the overlooked effect of heat on will make circuits of that size unreliable.

As chips get faster and carry out more calculations per second, they must also dissipate more energy.

"Today the chips are at the limit as far as power dissipation is concerned," said Kish.

To compensate for this, chipmakers have been decreasing chip voltage in order to keep power dissipation manageable, and making the chips more sensitive so that they work using the lower-voltage signals.

Amps are measures of electrical current, Watts are units of power, and voltage is the difference in electrical potential between two points in a circuit. The higher the voltage, the more Watts are produced per amp.

But as circuits continue to decrease in sin
ze and their supply voltage continues to grow weaker, energy generated by thermal noise, or heat, will start to interfere with electrical signals, which will increase chip errors, said Kish. "There is a fundamental interrelation between noise, information, speed and dissipation," he said.

Not only is there a limit to how low chip voltage can go, but that limit is closer than we think, said Kish.

Decreasing transistor size in the complementary metal oxide semiconductor (CMOS) chips used in most computers today from 100 nanometers to 40 nanometers will increase thermal noise by about a factor of three, which is enough to cause serious problems, said Kish. This means that the thermal noise is poised to become a serious issue at the beginning of the next decade, he said. "CMOS technology is close to [its thermal] limit," he said.

The effects could already be causing problems in today's smallest integrated circuit prototypes, according to Kish.

The significance of the temperature effect on digital circuits came as a surprise, and only came to light after detailed calculations connected with projects in nanoelectronics and nanotechnology, said Kish. "I expected something like that for nanoelectronics, [but the effect on CMOS chips] was a great surprise," he said. "I have... grown up with the belief that thermal noise is not an issue in digital circuits."

The thermodynamics problem has historically been overlooked because the original digital circuits were so big and slow that they had a very large tolerance for thermal noise. "It was obvious for everybody that thermal noise was not an issue," said Kish. Over time circuits have shrunk drastically in order to shorten the distances between circuits, which increases the number of calculations a chip can make in a second.

There's not a lot that can be done to get around the thermal limitation, said Kish. Today's silicon technology is the only commercially viable alternative for reaching the 40-nanometer size range by the end of the decade, he said.

It is possible to continue to successfully shrink the size of silicon transistors only if the clock frequency, or speed of the chip is decreased, said Kish. This could work if new chip architectures and software were developed that took greater advantage of parallel processing—using several chips at once to do the work of one, he said.

The results open up several questions, said Kish. Chip technology has remained largely the same for the past 30 years. The thermal limit may push the field toward entirely new architectures. One possibility is low-power computation. Another avenue is to look to biology, said Kish. "Can we do like the brain [and use] the noise for carrying the information?" he said.

There are many research efforts aimed at alternative chip architectures. There are two issues that may keep these architectures from emerging in practical devices very soon, however. Many are based on materials that are more expensive than silicon, the main substance of computer chips for the past three decades. And most would require completely new manufacturing processes.

Kish is currently working to understand the noise observation more closely, and relate it to similar observations on the quantum scale of atoms and particles. "I'm working on a paper which has a unified approach to quantum and classical information," he said.

Kish published the research in the December 2, 2002 issue of Physics Letters A. The research was funded by Texas A&M University.

Timeline: Unknown
Funding: University
TRN Categories: Integrated Circuits; Physics
Story Type: News
Related Elements: Technical paper, "End of Moore's Law: Thermal (Noise) Death of Integration in micro and nano electronics," Physics Letters A, December 2, 2002

Tinier Transistors Keep Moore's Law on Track

By Kimberly Patch, Technology Research News
December 20/27, 2000

A pair of research teams have independently shown that similar design modifications would allow transistors to be made as small as 10 nanometers, taking Moore's Law to about the year 2025.

Moore's Law says the number of transistors that can be crammed onto a computer chip doubles every 18 months. It is a prediction that computer chips have followed since they were invented around 1960. At several points in the past few decades, researchers have worried that this doubling, and the accompanying increase in chip speed, would slow as it finally hit up against the laws of physics.

Conventional wisdom says that it's likely to happen sometime within the next decade as the path electrons take through a transistor shrinks from today's state-of-the-art 100 nanometers to something less than 50 nanometers long.

This is because when presented with a channel less than about 50 nanometers, electrons are able to act like waves as well as particles and tunnel through it, continuing the flow of current whether or not the transistor is turned on.

The research teams, however, have concluded that double-gate field effect transistors (FET's) can block the flow of electrons in channels as short as 10 nanometers. University of California at Berkeley researchers have fabricated working, double-gate transistors as small as 15 nanometers.

A transistor usually has three gates—a pair of gates serve as the entrance and exit for the electron flow, and the third gate is a switch. Voltage flowing through the third gate opens the channel to electron flow, while turning off the voltage blocks electron flow in the channel. Double-gate transistors have four gates, and use gates positioned both above and below the channel to control the flow of electrons.

The gates effectively surround the channel with an electric field, which blocks electrons from tunneling through the channel until the distance between the entrance and exit gates shrinks to about 10 nanometers.

"The idea is to try to surround the conducting layer as much as possible," said Mark Lundstrom, a professor of electrical and computer engineering at Purdue University. "Putting a gate both on the top and bottom gives you a very strong electrostatic field that can block the flow of electrons between the other two terminals," he said.

The process is analogous to stopping blood from flowing in a vein, said Tsu-Jae King, an associate professor of engineering and computer sciences at the University of California at Berkeley and director of its microfabrication laboratory. "It is easier to stop blood flow if you pinch the vein from both sides, rather than to press it only from one side."

The Purdue team used tools designed to measure the electronics of molecules to figure out just how small the double-gate transistors could go. "What we've done is taken the theoretical framework that's used to explain experiments on conduction of molecules and applied [it] to transistors so we can really have a quantum-scale simulation that can address the problem [of] how small a transistor can be," said Lundstrom.

The simulation showed that the double gate would block tunneling down to about 10 nanometers, he said. In addition, because applications that do not require low power can likely tolerate a small amount of electron leakage through tunneling, they could potentially use transistors as small as eight nanometers, he said.

The industry will hit up against a size barrier using traditional transistors in five to seven years, Lundstrom pointed out. That leaves enough time to work out the trickier manufacturing process for the double-gate transistors, he said.

The manufacturing process that produces silicon devices usually starts with a piece of silicon and builds layers on it. "The tough part is figuring out the three-dimensional processing flow that can be used to put a gate on the bottom," said Lundstrom.

Although further optimization of the materials and the fabrication process is needed, the Berkeley team's basic design shows that it is possible to manufacture "high-performance sub-20 nanometer" transistors, said King.

The Purdue simulation is available for scientists and designers to use, said Lundstrom. "A lot of the commercial... computer-aided design tools don't take into account quantum phenomena. So we posted this on a web page so [they] can run those commercial tools on the simulation and compare the results," he said.

Lundstrom's research colleagues are Zhibin Ren, Ramesh Venugopal and Supriyo Datta of Purdue University, Dejan Jovanovic of Motorola and Los Alamos National Laboratory. The research was funded by Semiconductor Research Corp. (SRC) and the Defense Advanced Research Projects Agency (DARPA).

King's research colleagues are Jakub Kedzierski, Peiqi Xuan and Chenming Hu of UC Berkeley, Erik H. Anderson of Lawrence Berkeley National Laboratory, and Jeffrey Bokor of UC Berkeley and Lawrence Berkeley National Laboratory. The research was funded by DARPA.

Both groups presented their research at the International Electron Devices Meeting in December, 2000 in San Francisco.

Timeline: 5-7 years
Funding: Corporate, Government
TRN Categories: Integrated Circuits
Story Type: News
Related Elements: Technical papers, "The Ballistic Nanotransistor: A Simulation Study," and "Complementary Silicide Source/Drain Thin-Body MOSFETs for the 20nm Gate Length Regime," presented at the International Electron Devices Meeting (IEDM), December 11-16, 2000 in San Francisco; Purdue simulation, available at.nanohub.purdue.edu

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Stamps Bang out Silicon Lines

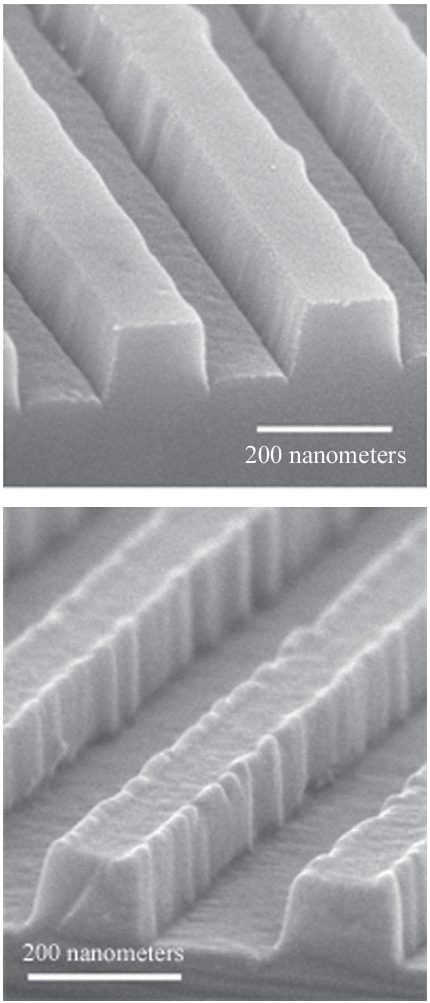
By Eric Smalley, Technology Research News
June 26/July 3, 2002

People have been pressing stamps into wet clay, soft wax and thin sheets of gold for thousands of years. Researchers at Princeton University have found a way to do the same with the wafers of silicon used to make computer chips, opening the way for this ancient technique to become the future of chipmaking.

The researchers' laser-assisted direct imprint (LADI) process uses a laser to melt microscopically thin layers of silicon, then presses a quartz mold into the molten silicon. Removing the mold from the cooled, re-solidified silicon leaves a precise imprint in the wafer.

The process takes less than one millionth of a second and can be used to create surface structures smaller than 10 nanometers. The high speed and ability to produce fine features make the process a promising candidate to replace today's minutes-long, more expensive, multistep photolithography chipmaking process, which uses light and chemicals to etch lines as thin as 65 nanometers into silicon. A nanometer is one millionth of a millimeter and 10 nanometers is the width of 100 hydrogen atoms.

"What distinguishes LADI from photolithography is its sub-10 nanometer resolution, its high speed and high-throughput processing, and its ability to directly pattern without the use of a [photo]resist or etching," said Chris Keimel, a researcher at Princeton.



Source: Princeton University

The quartz mold shown in the top image can be pressed into silicon melted by a laser to make ridges like those shown in the bottom image.

The researchers produced prototype patterns in silicon by etching microscopic lines and squares into one-millimeter-thick blocks of quartz, then pressing the blocks against the surface of silicon wafers and firing finely tuned ultraviolet laser pulses through the quartz molds. Quartz is transparent to the particular 308-nanometer wavelength ultraviolet light the researchers used, but silicon absorbs this wavelength and, as a result, heats up.

As the silicon wafers melted to a depth of about 280 nanometers, the liquid silicon rapidly filled the gaps in the mold. The researchers imprinted two patterns in silicon: a series of ridges 140 nanometers wide and 110 nanometers high, and raised squares 110 nanometers high and 8,000 nanometers on a side.

The researchers found 10-nanometer wide lines on the edges of the ridges formed by slight trenches in the corners of one of the molds, which proves that the process can eventually be used to make features smaller than are achievable using photolithography, said Keimel.

The process is quick because molten silicon flows with three times less resistance than water, which allows it to rapidly fill very small spaces.

The process could also be used to pattern other materials used in computer chips, said Keimel. Patterning computer chips' many layers of metals, semiconductors and insulators this way would require multiple lasers because different materials melt in different kinds of light. "Different materials absorb different wavelengths of light, so the laser source and material to be imprinted would need to be matched," he said.

Any fast, cheap process for producing computer chips has the potential to replace today's costly photolithography process, said Tsu-Jae King, an associate professor of electrical engineering and computer sciences at the University of California at Berkeley. "Lithography [is] the bottleneck in terms of cost and throughput for manufacturing integrated circuits," she said.

In theory, LADI could be used to form the tricky gate electrode layer in integrated circuits, said King. Gate electrodes are the silicon switches that turn transistors on and off, and getting their size and alignment right is critical in chipmaking, she said.

If the researchers' process can form new features in precise alignment with existing features on a silicon wafer, "then it should become a compelling choice for critical-layer patterning in integrated circuit manufacturing," said King. The process produces chip structures "at much lower cost than present-day optical lithography," she said.

LADI could be used for practical applications in three to five years, said Keimel. The researchers' next steps are to extend the technique to other materials and to apply it to large surfaces by moving the mold or surface regular intervals and repeating the stamping process, he said.

Keimel's research colleagues were Stephen Chou and Jian Gu, of Princeton University. They published the research in the June 20, 2002 issue of the journal *Nature*. The research was funded by the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research (ONR) and the Army Research Office (ARO).

Timeline: 3-5 years
Funding: Government
TRN Categories: Integrated Circuits, Semiconductors
Story Type: News
Related Elements: Technical paper, "Ultrafast and direct imprint of nanostructures in silicon," *Nature*, June 20, 2002

Sapphire Chips Linked by Light

By Kimberly Patch, Technology Research News
March 13, 2002

One of the challenges of making computer chips is efficiently ferrying information into and out of them. This is usually done via metal wires. Researchers from Johns Hopkins University have worked out a way to speed information to and from chips using light rather than wire.

The method is a way of using the fiber optics technology that make high-speed networks fast to bring information directly onto a chip. The ones and zeros of digital information are transmitted through wires using the absence or presence of electrical current. The same type of information is transmitted through fiber optics using the absence or presence of a pulse of light. Fiber optics is much faster than electronics, because pulses of light can be sent through fiber much faster than an electrical switch can flip on and off.

To transmit information to a chip using light, the researchers had to change the structure of the chip. The new design could speed information transfer on and off chips by five times.

Computer chips are usually made up of thin slices of the semiconductor silicon. The researchers added layers of synthetic sapphire, an insulator that does not conduct electricity, but allows light to pass through.

They used microlasers to beam light perpendicular to the plane of the wafer, and bonded microdetectors onto the sapphire layer of the chip to pick up the light transmissions. "The light is transmitted through the plane of the electronics," said Alyssa Apsel, a graduate student at Johns Hopkins University.

Once the signal reaches its destination, it goes through an optical receiver that transforms the light signal back to an electrical signal that can be handled by the chip's electrical wiring.

The researchers' prototype is capable of shunting information on and off the chip at the rate of one gigabit per second, according to Apsel. Four minutes of full-motion video contain about one gigabit of information.

As the parts of the chip get smaller, chip communications get faster because information does not have as far to travel. The components of the researchers prototype are half a micron wide. The next generation of the researchers chip will have features as small as 0.1 microns, a size equivalent to today's production electronics, said Apsel. A micron is one thousandth of a millimeter.

At 0.1 microns, the researchers' design has the potential to run at 5 gigabits per second, said Apsel. Today's production computer chips have bus speeds that are generally below one gigabit per second. The design is also fairly power efficient, according to Apsel. The 0.5 micron prototype uses about 10 microwatts, and the next generation may use less, she said.

The new chip design could be used to improve the internal rates of data transfer among chips in a computer. It could also be used to improve the speed of information transfer in future Local Area Networks, said Apsel. There is also a biological application, she added. “There are uses in biological sensory systems... which require a higher level of circuit-to-circuit connectivity than current systems are capable of,” she said.

The researchers are working on improving the efficiency of their design, and producing larger arrays of opto-electronic links. “We would like to ultimately build very high-performance systems using optical interconnects,” said Apsel.

It will be a few years before the technology can be made practical, Apsel said.

Apsel’s research colleague is Andreas Andreou. They published the research in the third quarter, 2001 issue of the IEEE Circuits and Systems magazine. The research was funded by the Army Research Laboratory (ARL) and the Defense Advanced Research Projects Agency (DARPA).

Timeline: 3-5 years
Funding: Government
TRN Categories: Optical Computing, Optoelectronics and Photonics;
Integrated Circuits
Story Type: News
Related Elements: Technical paper, “Silicon on Sapphire CMOS for Optoelectronic Microsystems,” IEEE Circuits and Systems magazine, third quarter, 2001

Crossed Nanowires Compute

By Eric Smalley, Technology Research News
November 14, 2001

A simple calculator that adds binary numbers may herald the end of computer chips as we know them.

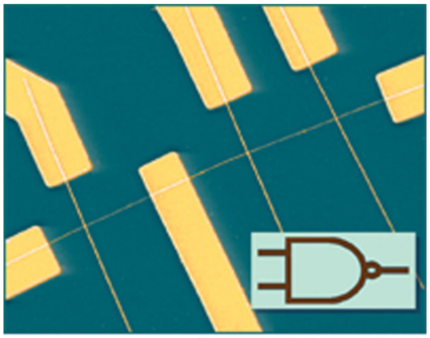
Researchers at Harvard University assembled the rudimentary computer out of nanowires 3,000 times finer than human hair using a simple manufacturing process. The process could make computers that are small and cheap enough to be built into everything from tires to wallpaper.

The nanowire design could be ready for practical use before today’s silicon technology loses out to the laws of physics in the quest to make smaller and faster transistors.

The breakthrough was being able to form a transistor simply by crossing two of the nanowires. A silicon nanowire carries electrical current when a perpendicular galium nitride nanowire lowers the silicon nanowire’s electrical resistance, turning the transistor on.

“We have developed a... crossed-nanowire field effect transistor that is readily amenable to high-density integration without the use of lithography,” said Charles Lieber, a chemistry professor at Harvard University.

Today’s computer chips are made using photolithography, a process that uses light and chemicals to etch lines into silicon wafers. The process requires vacuum chambers, powerful lasers and hazardous chemicals, which is why state-of-the-art chip factories tend to be billion-dollar facilities.



Source: Lieber Group, Harvard University

These nanowires, each 3,000 times finer than a human hair, form a NOR logic gate. Computer chips are made of thousands of logic gates. The inset in the lower right corner is the NOR gate symbol.

The best photolithography techniques produce wires as narrow as 130 nanometers, and fit 10 to 100 million transistors on a square centimeter of silicon. The researchers’ process will allow several orders of magnitude more transistors to be crammed onto a chip than semiconductor technology is predicted to provide even a decade from now, said Lieber.

The nanowire transistors could be packed one billion to a square centimeter, and narrower nanowires would permit one trillion transistors per square centimeter, he said.

Transistors are electronic switches that turn current on and off to represent the ones and zeros of computing. The researchers combined nanowire transistors to form several types of logic gates, which use these on and off states to do calculations. They made simple logic gates that performed OR, AND and NOR logic functions. An OR gate turns on if either or both of two inputs are on, an AND gate turns on if both inputs are on, and a NOR gate turns on if both inputs are off.

The researchers also combined these simple logic gates to form more complicated logic units, including a half adder, which adds binary numbers together. Computer processors are made of combinations of these more complicated logic units.

The researchers built the transistors by chemically growing silicon and galium nitride nanowires 10 to 30 nanometers in diameter and several microns long. They coaxed the nanowires to form circuits by suspending them in fluid and flowing the mixture across a surface. The tiny wires line up in the direction of the flow. They placed the silicon nanowires in one direction and the galium nitride nanowires in a perpendicular direction.

Simply putting the wires in place was enough to assemble the gates: the nanowires are so small that atomic forces make them stick when they touch.

Semiconductor nanowires make good computer chip building blocks because their long, narrow shape and good electronic properties enable them to be used both as wiring and to make functional devices like transistors, said Lieber. The researchers' nanowire transistors boost electrical signals as they pass through, which makes it possible for many of them to be connected without the signal fading away.

Though the researchers were able to build the logic gates chemically, they had to connect groups of gates using lithographically-formed electrodes, and they had to position the nanowire logic gates on the electrodes by hand. The researchers are currently working on assembling the nanowires directly on the electrodes, said Lieber.

They are also looking to connect the logic units nanowire-to-nanowire, which would make it possible to build entire computer chips using only the chemical assembly technique, he said.

Ultimately, chip factories could boil down to microscopic channels and reservoirs. "In the alignment and placement phase of nanowires... microfluidic machines [could be] the critical fabrication-line tool," said Lieber.

The results are exciting because the researchers coaxed transistors to self-assemble, said James S. Harris, an electrical engineering professor at Stanford University. "The most exciting result is that they could deposit these wires in an interconnected 3-D matrix, creating a true 3-D integrated circuit."

However, the researchers will have to use a different chip architecture than the one used by today's computer chips, said Harris. Their architecture will have to be very highly parallel because the nanowires have high electrical resistance, which means circuits made from them will operate at relatively low clock rates compared to today's integrated circuits. "It will win only by extremely high density and parallelism, not speed," he said.

The nanowire process should be able to produce complicated integrated circuit devices in 5 to 10 years, said Lieber.

Lieber's research colleagues were Yu Huang, Xiangfeng Duan, Yi Cui, Lincoln J. Lauhon and Kyoung-Ha Kim of Harvard. They published the research in the November 9, 2001 issue of the journal *Science*. The research was funded by the Office of Naval Research and the Defense Advanced Research Projects Agency (DARPA).

Timeline: 5-10 years
Funding: Government
TRN Categories: Nanotechnology; Integrated Circuits; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Logic Gates and Computation from Assembled Nanowire Building Blocks," *Science*, November 9, 2001

Tiny Tubes Make Logic Circuits

By Kimberly Patch, Technology Research News
October 10, 2001

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

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

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

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

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

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

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

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

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

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

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

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

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

The researchers have made a "major advance" in nanotube logic circuits, said Steven Kornguth, assistant director of the Institute for Advanced Technology at the University of Texas. Key to the advance is the nanotube transistors better transconductance. "The advance realized is a gain in voltage, or signal output by a factor of 10," he said.

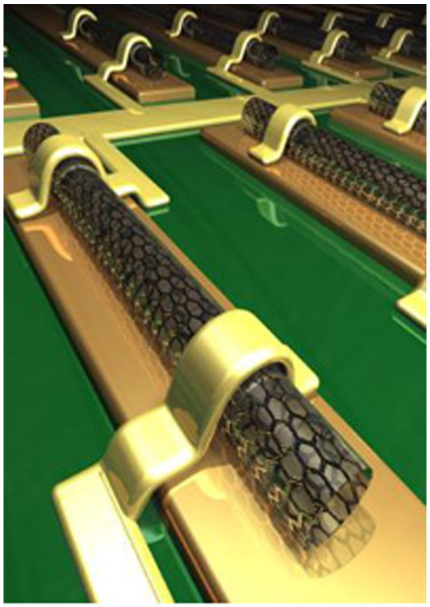
The Delft and IBM advances show that, in principal, it is possible to make practical logic devices from carbon nanotubes, said Michael Fuhrer, an assistant professor of physics at the University of Maryland.

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

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

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

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


Source: Delft University

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

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

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

Coax Goes Nano

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

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

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

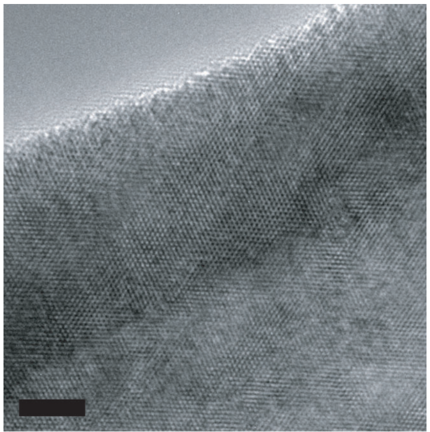
The layered wires are new building blocks for nanotechnology, according to Charles Lieber, a professor of chemistry at Harvard University. The vanishingly small nanowire components could be used to make faster computer chips, higher-density memory and smaller lasers.

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

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

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

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



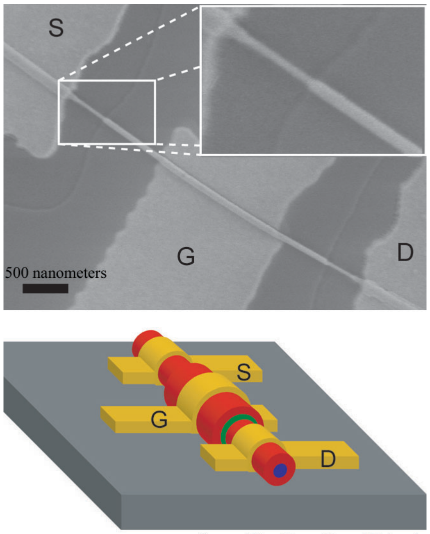
Source: Lieber Group, Harvard University

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

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

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

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



Source: Lieber Group, Harvard University

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

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

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

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

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

Most nanoscale electronic devices made from carbon nanotubes or nanowires are oriented lengthwise, Wang said. The Harvard work shows for the first time that the different layers that make up field-effect transistors and other devices can be positioned across the width of nanowires, he said.

"This research demonstrates the possibility of building much smaller devices based on nanowires," he said

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

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

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

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

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

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

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

Timeline: 2-5 years
Funding: Government
TRN Categories: Nanotechnology; Integrated Circuits; Semiconductors; Materials Science and Engineering; Chemistry
Story Type: News
Related Elements: Technical paper, "Epitaxial core-shell and core-multishell nanowire heterostructures," *Nature*, November 7, 2002

Tiny Wires Turn Chips Inside Out

By Eric Smalley, Technology Research News
February 13, 2002

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

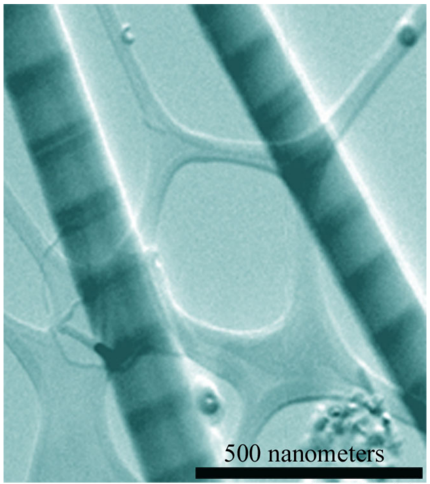
Computer chips, lasers and many other modern electronic devices are made by etching circuits into microscopically thin layers of semiconductor materials using narrow beams of light. Narrower beams make smaller circuits, and smaller circuits make faster devices. There is a limit to how narrowly a light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

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

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

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

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



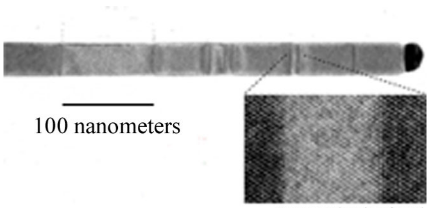
Source: UC Berkeley

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

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

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

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



Source: University of Lund

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Yang's research colleagues were Yiying Wu and Rong Fan of the University of California at Berkeley. They published their results in the February issue of Nano Letters. Their work was funded by the National Science Foundation

(NSF), U.S. Department of Energy (DoE) and the University of California at Berkeley.

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

Nanotube Kinks Control Current

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

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

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

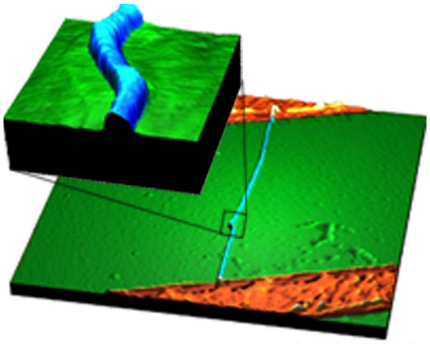
To create the nanotube transistor, the researchers used an atomic force microscope (AFM) to put two kinks in a nanotube. "We have strongly bent, or buckled, a nanotube twice with an atomic force microscope. In this way, we created an ultra-tiny conducting island within the nanotube," said Cees Dekker,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

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

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

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

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


Source: Delft University

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

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

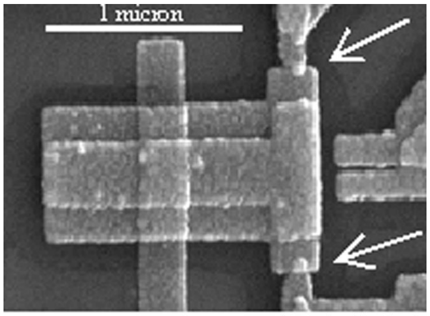
In a transistor, electrons flow from a source electrode to a drain electrode through the island. At two ends of the island are junctions that connect the island and the electrodes. On either side of the island are gates. When there is no voltage moving through the gates, electrons are blocked from moving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

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

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

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

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



Source: Pieter Heij, Delft University

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

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

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

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

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

Jolts Yield Nanotube Transistors

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

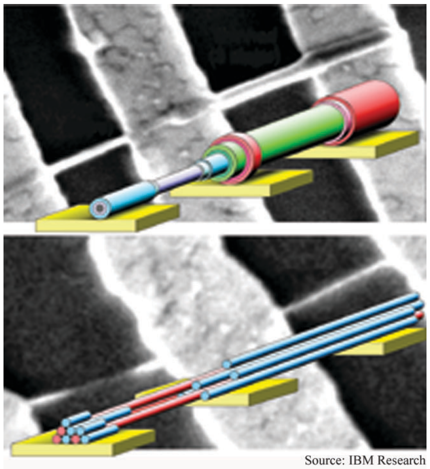
Today’s Pentium IV chips, for example, sport about 42 million transistors with features as narrow as 180 nanometers. Computer chips use transistors to form the circuits that perform basic logic functions, and in order to continue to build faster, more powerful computers, chip manufacturers must cram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

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

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

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

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



Source: IBM Research

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

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

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

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

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

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

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

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

Spot of Gold Makes Tiny Transistor

By Chhavi Sachdev, Technology Research News
November 21, 2001

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

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

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

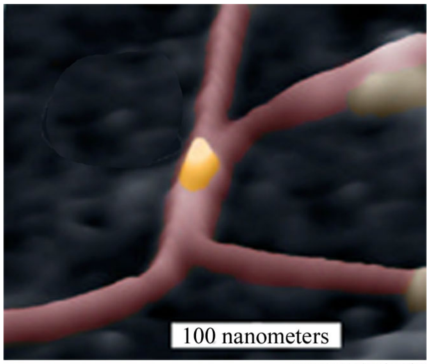
Manipulation of such tiny objects is a delicate process. The researchers managed to position a carbon nanotube between two electrodes using an atomic-force microscope (AFM) tip. Then they used the tip to cut the nanotube—a rolled-up sheet of carbon atoms—into two sections, “each section still in contact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

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

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

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

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



Source: Lund University

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

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

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

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

Nanotubes Grown in Place

By Eric Smalley, Technology Research News
August 7/14, 2002

Research in recent years has generated a lot of excitement about carbon nanotubes, those infinitesimal tubes formed of carbon sheets a mere one atom thick. The more researchers find out about them, it seems, the more potential uses they gain.

Nanotubes are extraordinarily strong, conduct electricity, vibrate at high frequencies, emit light, and are sensitive to the presence of minute amounts of substances.

But there's a lot of hard work to be done before the average person routinely uses devices that contain nanotubes. Getting the thread-like molecules to form in specific places, for instance, is a formidable challenge.

Stanford University researchers have made this easier with a method for growing individual tubes directly between pairs of electrodes. The researchers built arrays of metal electrodes, then coaxed nanotubes to form, suspended, in the gaps between them, said Hongjie Dai, an assistant professor of chemistry at Stanford.

The technique could be used to produce several types of electronic components, said Dai. Nanotubes' microscopic size and very long, thin shape mean they are able to vibrate extremely rapidly, and rapidly vibrating nanotubes are sensitive to subtle changes.

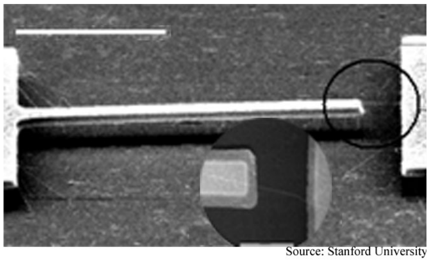
This ability could make them useful as sensors that measure forces like acceleration, and for tuning radio waves in communications devices. They could be used in chemical sensors; strain gauges; electromechanical transducers, which convert sound, pressure or light to electrical signals; and high frequency mechanical resonators for telecommunications applications like cell phones, according to Dai.

A common laboratory method for producing nanotubes, which occur naturally in small amounts in soot, is to cause carbon to condense out of a hot vapor of chemicals. It is difficult, however, to use this method to get nanotubes to grow in the specific locations and orientations needed to form electrical components.

In contrast, the Stanford method allowed the nanotubes to form between metal electrodes the researchers had added to a silicon wafer using photolithography, the process of etching materials with light and chemicals that is used to make computer chips.

The resulting nanotubes were 2.5 nanometers in diameter and spanned electrode gaps ranging from 3,000 to 10,000 nanometers. A nanometer is one millionth of a millimeter. The longest of the nanotubes were as long as the width of two red blood cells, but were 2,000 times narrower than a single red blood cell.

The researchers used the metal molybdenum for the electrodes and added small amounts of iron to encourage the nanotube growth process. They found that molybdenum both survived the high-temperature nanotube growth process and did not inhibit nanotube growth, according to Dai. Using the metals gold, titanium, tantalum or tungsten resulted either in faulty electrodes or no nanotubes.



Source: Stanford University

The thread-like object in this electron microscope image is a suspended nanotube bridging a silicon cantilever and terrace.

The researchers were able to get single nanotubes to form between electrodes 30 percent of the time, and were able to get multiple nanotubes to span the gaps 90 percent of the time, according to Dai.

Some of the suspended nanotubes worked as transistors, which control the flow of electricity in computer chips. The suspended nanotube transistors were comparable to those grown on flat surfaces using more common techniques, according to Dai.

The researchers also used a nanotube to electrically connect a cantilever to a silicon surface. Making a precise connection between a nanotube and a moving part allowed the researchers to test the nanotubes' electromechanical properties, said Dai. For instance, the researchers found that a nanotube's resistance to the flow of electricity increased when they stretched it, he said.

The work is important because it allows researchers to grow nanotubes directly in electrical and electromechanical devices, said Paul McEuen, a physics professor at Cornell University. "You can grow them where you want them." Other approaches to integrating nanotubes and electronics involve processing steps that occur after the nanotube are grown, which can damage the nanotubes, he said.

The researchers' technique could be used in practical applications in two to five years, said Dai. The next steps in their research are carrying out studies of the tubes' basic electromechanical properties studies and making nanoelectromechanical devices, he said.

Dai's research colleagues were Nathan Franklin, Qian Wang, Thomas Tombler, Ali Javey and Moonsub Shim. They published the research in the July 29, 2002 issue of *Applied Physics Letters*. The research was funded by the Defense Advanced Research Projects Agency (DARPA), the Semiconductor Industry Association, The David and Lucile Packard Foundation, and the Alfred P. Sloan Foundation.

Timeline: 2-5 years
Funding: Government, Corporate, Private
TRN Categories: Chemistry; Integrated Circuits; Materials Science and Engineering; Nanotechnology
Story Type: News

Related Elements: Technical paper, “Integration of suspended carbon nanotube arrays into electronic devices and electromechanical systems,” *Applied Physics Letters*, July 29,

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Nanotube Chips Draw Near

By Eric Smalley, Technology Research News
February 20, 2002

Carbon nanotubes are all the rage in research circles because they are versatile and very small. But before these rolled-up sheets of carbon atoms can take the rest of the world by storm researchers have to make millions of them at a time in orderly arrays and connect them to form useful devices.

Carbon nanotubes usually form in a jumble, like a pile of cooked spaghetti. The challenge is to get them to form in the right places, and grow straight and in the right direction.

Researchers at Stanford University have coaxed massive arrays of single-walled carbon nanotubes to form on specific sites on the 4-inch silicon wafers used to make computer chips. Growing nanotubes in an orderly fashion on silicon wafers makes it possible for manufacturers to use existing chipmaking technology to connect the nanotubes into circuits.

The technique could eventually be used to produce massive transistor arrays for computer processors, memory chips and chemical and biological sensors, said Hongjie Dai, an assistant professor of chemistry at Stanford University. “Full wafer growth enables scalability of nanotube devices,” he said.

To make the nanotubes grow on a wafer, the researchers used photolithography, an etching method that employs light and chemicals, to put an array of 10 to 100 million microscopic dots on the silicon wafer. The dots, which are as small as one micron in diameter, served as catalysts to initiate the growth of carbon nanotubes. A micron is one thousandth of a millimeter; a red blood cell measures 5 microns in diameter. The researchers then exposed the wafer to a hot vapor containing carbon. The carbon atoms condensed to form nanotubes and began their growth from the catalyst dots.

The researchers used electric fields to orient the nanotubes as they grew, said Dai. The nanotubes acted like microscopic magnets that were oriented with electric field.

One, two or three single-walled nanotubes grew from each dot, according to Dai. The nanotubes ranged from 1 to 3 nanometers in diameter and grew as long as 10,000 nanometers, which is about twice as long as a red blood cell. A nanometer is one millionth of a millimeter and one-thousandth of a micron.

The chemistry that yields the nanotubes is independent of the size of the catalyst islands, and the technique could theoretically produce a nanotube for every 100 square nanometers of surface area on a wafer, or about 800 million on a 4-inch wafer, said Dai.

The researchers’ next step is using standard chip-making techniques to place metal contacts over the nanotubes to connect them into circuits, said Dai. The patterned nanotube growth technique could find using practical applications in 1 to 5 years, said Dai.

Dai’s research colleagues were Nathan Franklin, Yiming Li, Robert Chen and Ali Javey of Stanford University. They published their research in the December 31, 2001 issue of the journal *Applied Physics Letters*. The research was funded by the Defense Advanced Research Projects Agency (DARPA).

Timeline: 1-5 years
Funding: Government
TRN Categories: Materials Science and Engineering; Nanotechnology; Integrated Circuits
Story Type: News
Related Elements: Technical paper, “Patterned growth of single-walled carbon nanotubes on full 4-inch wafers,” *Applied Physics Letters*, December 31, 2001; “Electric-field-directed growth of aligned single-walled carbon nanotubes,” *Applied Physics Letters*, November 5, 2001

Nanotube Array Could Form Chips

By Ted Smalley Bowen, Technology Research News
January 23, 2002

The imperative to shrink all things electronic has led researchers to fashion transistors from carbon nanotubes, which are thousands of times thinner than a human hair. But before these minuscule components can find their way into computer chips or other devices they must be produced en masse.

A group of researcers from the Samsung Advanced Institute of Technology and the Chonbuk National University in Korea has made nanotube field-effect transistors in bulk by growing them in vertical bunches, then using electron beam lithography and ion etching to make the source, gate and drain electrodes that control the flow of electrons.

These high-density arrays of transistors can be controlled with little energy, according to Won Bong Choi, project manager at the Samsung Advanced Institute of Technology.

The multi-walled nanotubes, which are sheets of carbon atoms rolled up into tubes, measure 20 nanometers wide. A nanometer is one millionth of a millimeter. Two trillion of the transistors would fit into a square centimeter.

The arrays of tiny transistors could eventually be used to make smaller, faster computer chips and very sensitive sensors, according to Choi.

To make the arrays, the researchers deposited a layer of silicon dioxide on an aluminum oxide plate, then used a beam of electrons to mark a grid of microscopic dots on the surface, and applied chemicals to eat away the marks to form pores in this template. The researchers released a hot vapor containing carbon into the pores to form the nanotubes.

They added source, drain and gate electrodes to the nanotubes by applying silicon dioxide lines across the grid of nanotubes, using electron beam lithography and ion milling to etch the silicon dioxide, then adding gold and titanium to form the electrodes. In ion milling, high-energy ions are fired at a surface to eject individual atoms of the surface material.

The source electrodes are essentially rows across the bottom of the carbon nanotubes, and the drain electrodes are perpendicular rows across the top of the nanotubes. The gate electrodes are also near the top of the nanotubes. In field-effect transistors the gate electrodes control the flow of electrons through the transistor. When current is applied to the gate electrode, the resulting electrical field turns the transistor on, and electric current flows from the source to the drain electrode.

The researchers' carbon nanotube transistors worked at temperatures up to an extremely cold -243 degrees Celsius, according to Choi. The transistors will need to work at much warmer temperatures to be used in practical devices.

The vertical alignment of the nanotubes allows many nanotubes to be packed in the small spaces needed for producing small, dense electrical components. The method also allows for close control of the the manufacturing process, said Choi. It allows fabricators to "control the position of carbon nanotubes, manipulate [them, and] control [their] diameter and thickness," he said.

Conventional transistors are typically made of layers of silicon or germanium semiconductor material that have different electrical properties due to small amounts of impurities - usually boron, arsenic, or iridium. The electrical properties of carbon nanotubes can be altered by varying the angle at which the carbon atoms are aligned.

Transistors are used as amplifiers, oscillators, photocells and switches, which are the key component of the integrated circuits that make up computer chips. Computers use the on and off states of transistors to represent the ones and zeros of binary code.

The researchers' method is still very rough, and they did not demonstrate that individual transistors could be accessed, according to Zhen Yao, assistant professor of physics at the University of Texas.

"Each nanotube can in principle be addressed using a source line at the bottom and a drain line at the top. However, the authors didn't really demonstrate that they could address individual nanotubes. Instead, the field-effect transistor characteristics were measured over the entire array of nanotubes," he said.

In addition, the level of current running through the array is very low, said Yao. The transistors' structure and materials are part of the problem, he said.

"Because the transistor gate, which controls the flow of electrons through the source and drain electrodes, was placed over the ends of the vertically-aligned nanotubes, "the gate coupling would be too weak for practical device operations," said Yao. In addition, the nanotubes contain a lot of defects, which makes them difficult to analyze electrically, he said.

The nanotubes rough composition limits their use, said Yue Wu, associate professor of physics at the University of North Carolina. "The carbon nanotubes are very defective. The device won't work at room temperature because the tubes are not clean semiconductors," he said.

Nonetheless, carbon nanotubes sensors that use the arrays could be possible within five years, and computer memory chips made with the process could be practical by 2010, said Choi.

Choi's research partners were Jae Uk Chu, Kwang Seok Jeong, Eun Ju Bae, and Jo-Won Lee of the Samsung Advanced Institute of Technology, and Ju-Jin Kim and Jeong-O Lee of the Chonbuk National University Department of Physics. They published the work in published in the November 26 issue of *Applied Physics Letters*. The work was funded by Korean Ministry of Science and Technology.

Timeline: 5-8 years
Funding: Government
TRN Categories: Semiconductors; Integrated circuits; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Ultrahigh-density nanotransistors by using selectively grown vertical carbon nanotubes", *Applied Physics Letters*, November 26, 2001

Chemists Brew Tiny Wires

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

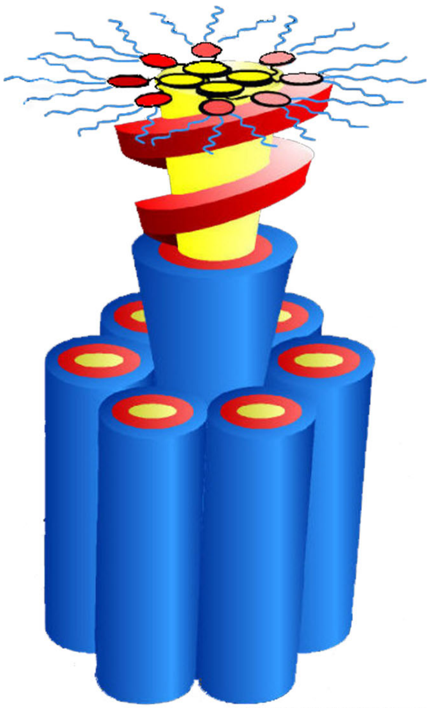
There are two ways to make the smaller circuits and electronic components that promise to underpin tomorrow's technologies: improve today's top-down approach of using tools to manufacture circuits, and develop a bottom-up approach of having the circuits build themselves molecule by molecule.

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.


Source: University of Pennsylvania

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

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

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

The dendrimers electrically insulate and keep moisture away from the electrically-conductive columns. The method could be used with many kinds of conductive materials, said Percec. “A large variety of electronically active molecules can be incorporated in the center of the cylinders.”

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

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

Mixes Make Tiniest Transistors

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

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

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

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

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

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

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

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

The Cornell molecule has a single cobalt atom at its center and all of the electrons flow through the atom. "We can regulate electronic flow at the scale of a single atom," said Ralph. The Harvard molecule consists of a pair of atoms of the metal vanadium.

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

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

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

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

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

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

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

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

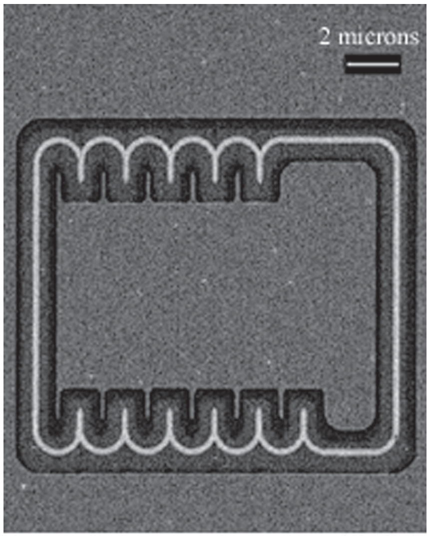
Timeline: >5 years, 10-20 years
Funding: Government, Private
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Nanotechnology
Story Type: News
Related Elements: Technical papers, "Coulomb blockade and the Kondo effect in single-atom transistors," *Nature*, June 13, 2002 and "Kondo resonance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

Bent Wires Make Cheap Circuits

By Kimberly Patch, Technology Research News
June 26/July 3, 2002

Today's computers use the presence or absence of a flow of electrons to represent the ones and zeros of binary logic, and they detect this current by sensing electrical charge. There's more to electrons than charge, however. They also have spin, a magnetic property similar to the two poles of an ordinary refrigerator magnet.

Magnetic spin is already used to store information in the microscopic bits of disk drives and in a recently-developed magnetic memory chip. Using spin to compute as well would pave the way for all-magnetic, cheap, low-power computers. And because the spin states of electrons remain stable even when the power goes off, such a computer would not have to boot up every time it is turned on.



Source: Durham University

This logic circuit, which is made up of 11 NOT gates, processes magnetic rather than electronic bits.

Current spintronics efforts generally focus on using spin to carry out the logic operations of computing by moving electrons around while preserving their spins.

Another way to move a spin signal, however, is to find a way to ripple the signal through a series of stationary electrons, similar to the way a row of dominos affects each other. Carrying out the logic operations of computing this way requires moving the magnetic domain wall—the region along a wire where magnetization changes direction—through a series of logic circuits.

Researchers from Durham University in England have taken a large step in this direction by constructing a NOT gate—one the basic logic circuits of computers—that carries out a computation using the spin of electrons. "You replace the high-voltage/low-voltage representation of the numbers one and zero with North pole/South pole," said Russell Cowburn, a lecturer in physics at Durham University.

Information flows when a spin flips its direction, and then causes its neighbors to flip. "Instead of sending voltage... around the chip, you send magnetic domain walls," said Cowburn.

A NOT gate changes an input signal to its opposite; when a one goes through a NOT gate it comes out as a zero, and vice versa. "The NOT gate is just a nanoscale magnetic wire that is [bent] into a hairpin so that as the domain wall moves around it, the magnetiza-tion direction is reversed," said Cowburn. The path that reverses the direction of magnetization is similar to the path a car takes when it does a K-turn to reverse direction.

The researchers designed the logic circuit after realizing that they could drive domain walls around a tiny magnetic circuit using a rotating magnetic field, said Cowburn. "We found that the sense of rotation—clockwise or counter-clockwise—is really important and can be used to give you immense control over the flow of information," said Cowburn.

To fabricate such circuits, the researchers had to make extremely small, smooth wires. "We had to perform some very accurate metal fabrication—making magnetic wires with edges that are smooth to within 10 or 20 nanometers," Cowburn said. A nanometer is one millionth of a millimeter, or about the size of a line of 10 carbon atoms.

In order to see that the circuit was working, the researchers had to find a way to measure whether the signal had changed. They developed a laser that measures magnetic signals the same way an oscilloscope measures electric signals. "You just drop the laser beam onto the part of the spintronics circuit that you want to probe, and the magnetic waveform appears on the computer screen," said Cowburn.

The researchers also built a larger circuit consisting of 11 NOT gates to show that the gates can be linked together. The circuits formed a shift register, which computers use to change the position of a series of binary digits. Shifting the number 100 one place to the left, for example, yields 1000. Shifting it one place to the right yields 10.

The researchers are currently working on an AND gate, which has two or more inputs, and returns a one rather than a zero only if all of the inputs are one. The NOT and AND gates are the basic building blocks of computer logic. "Once we've got [the AND gate] we could build any circuits that could be built from conventional digital logic," said Cowburn.

Ultimately, the researchers are aiming to make a spin-based computer chip that "does all the things that conventional electronic chips do, but with the cost, power, size and non-volatility advantages that come from magnetic logic," said Cowburn.

The researchers' spin design can potentially make for extremely small chips that are relatively inexpensive to manufacture because the circuits are made from single wires rather than semiconductor transistors, said Cowburn. Semiconductors are shaped using chemicals and light to peel away layers of material. The researchers devices, however, can be made from a single layer, eliminating the need to align multiple layers, which is one of the costliest processes in chip manufacture.

The simpler wire-based circuit design is also a good candidate for self-assembly processes, where materials are built molecule-by-molecule using mixes of chemicals, similar to the way biological organisms are made. Eventually, "it should be possible to shrink the devices to much smaller sizes—possibly close to the atomic scale," Cowburn said.

The amount of power needed to shunt domain walls around would be considerably less than is needed for electrical current, making spin circuits potentially useful for small mobile devices like phones and smart cards, said Cowburn. “The ballpark is in the range [of] 100 to 1000 times lower power,” he said.

In the distant future the devices could be implanted inside the human body to, for example, monitor biological functions, he said. The devices would require so little power they could be supplied from a small electric coil placed outside of the body that would surround the spin circuits with an electromagnetic field, rather than having to wire it directly to a power source, according to Cowburn.

The research is an interesting twist on well-established physics, according to Jay Kikkawa, an assistant professor of physics at the University of Pennsylvania. “While it is known that magnetic fields can transmit a wall from one end of a wire to the other, the authors show that the shape of the wire can invert the wall en route,” he said.

What is needed next are similar geometrical concepts that can be used to form more complicated logic gates, according to Kikkawa. “With a few additional innovations, computing elements could be constructed for certain non-volatile applications. I’m particularly interested to see how the fidelity of these gates will hold up at higher gate speeds and densities,” he said.

Simple spin devices could be made practical within the next two years, Cowburn said. “More complicated devices will take a little longer—probably five years,” he said.

Cowburn’s research colleagues were Dan A. Allwood, Xiong Gang, Michael D. Cooke, Del Atkinson, Colm C. Faulkner and Nicolas Vernier. They published the research in the June 14, 2002 issue of the journal *Science*. The research was funded by the private engineering investment company.

Timeline: 2-5 years
Funding: Corporate
TRN Categories: Integrated Circuits, Physics, Spintronics
Story Type: News
Related Elements: Technical paper, “Submicrometer Ferromagnetic NOT Gate and Shift Register,” *Science*, June 14, 2002

Magnetic Transistor Means Changeable Chips

By Kimberly Patch, Technology Research News
March 12, 2001

Transistors allow electrons to flow through them in a controlled way. It is this controlled flow of electrons that provides the on-off signals that are the basis of computing.

Electronic transistors control this flow of electrons by putting a barrier, or junction in front of them, and then adding current to allow them to hop over it.

But the flow of electrons doesn’t necessarily have to be controlled by adding current. Physicists from the Universities of Iowa and Missouri are proposing a type of transistor that uses the magnetic spin of electrons to switch the flow of electrons on and off.

Magnetic spin transistors would work in a way similar to today’s electronic transistors, with one potentially large advantage: they could be created as easily as writing information onto a magnetic disk. Computer chips made with magnetic spin transistors could therefore be reconfigured.

Ordinary electronic transistors have three electrodes, which carry current. The electrons enter through one of the electrodes, exit through another, and the third controls the electron flow through the other two.

The key to an electronic transistor is its n-p-n junction—the way the electrons are arranged around the atoms of the p portion of the material provides a barrier that electrons can pass through only when they have enough energy. Putting current through the controlling electrode allows the electrons to flow over the junction.

The plans for a magnetic spin transistor call for using the difference between spin up and spin down electrons to control electron flow. Electrons can be thought of as tiny spinning tops with a magnetic field oriented along the spin axis. The electrons can be in one of two states—spin up or spin down.

In the spin transistor, the barrier would be a portion of the material whose magnetic domain has the opposite magnetization as the carriers, or electrons with one of the two spin and orientations. “The thing about magnetic semiconductors is they have different energies for carriers that spin up and spin down. We’re using that to [change] the barrier,” said Michael Flatté, an associate professor of physics at the University of Iowa.

The idea behind the spin transistor is not to use it in place of electric transistors, but to use it where it can provide something more, said Flatté.

Because the barriers in spin transistors are magnetic, they can be changed, enabling, in effect a chip configuration that can be changed as easily as rewriting data on a magnetic disk. “You could have in some sense a universal chip [that] you can configure any way you want,” said Flatté.

For instance, a certain region of this type of chip could start out as a wire, with the same magnetization all across the region. Then, by reorienting the magnetization of the middle part of the region to have the opposite magnetization “you create a domain wall and now you have essentially a transistor,” he said.

Shuffling around the wires and transistors on a chip could be done in two distinct ways, Flatté said. “A structure similar to a write head for a hard disk could do this... or you could have built-in writing regions, which would be faster but it involves a lot more processing—you would have to integrate writing wires into the system as well," he said.

Spin transistors could also be used as nonvolatile memory, Flatté said. Magnetic nonvolatile memory could turn out to be cheaper than today's standard nonvolatile memory because the signals could be detected without having to use additional transistors to amplify them, he said.

The idea of a magnetic transistor is not entirely new, but the way the researchers have worked out the fundamental research is good, said Manijeh Razeghi, a professor of electrical and computer engineering and director of the Center for Quantum Devices at Northwestern University.

Going from this proposal to an actual spin transistor is a potentially difficult road, however, she said. "The idea is good but the challenging part is the materials and the fabrication," said Razeghi.

There is potential on the materials side, according to Flatté. A new material that looks like it could meet the spin transistor requirements was made by a team of researchers based at the Tokyo Institute of Technology, who reported their results in the February 2, 2001 issue of *Science*. The researchers doped titanium dioxide with cobalt to make an n-doped ferromagnetic semiconductor.

There are still unknowns about using this material for spin transistors, he said. One key question is how distinct the opposite spin positions of the electrons are in the material. Another is how thin the junction between the spin up and spin down sections of the transistor can be made. The thinner the barrier, the more easily the transistor can be controlled.

If the titanium dioxide cobalt material turned out to work reasonably well, a magnetic transistor based on this idea could be produced in less than five years, Flatté said.

The researchers are continuing to look for appropriate materials to use in magnetic transistors. They are also working out how far apart the spin directions need to be in order to be reliably detected, he said.

Flatte's research colleague was Giovanni Vignale of the University of Missouri. They published the research in the February 26, 2001 issue of *Applied Physics Letters*. The research was funded by the National Science Foundation (NSF).

Timeline: > 5 years
Funding: Government
TRN Categories: Semiconductors and Materials
Story Type: News
Related Elements: Technical paper, "Unipolar Spin Diodes and Transistors," *Applied Physics Letters*, February 26, 2001; Technical Paper, "Room-Temperature Ferromagnetism in Transparent Transition Metal-Doped Titanium Dioxide," *Science*, February 2, 2001

Logic Scheme Gains Power

By Eric Smalley, Technology Research News
February 12/19, 2003

Researchers from the University of Notre Dame have pushed an alternative computer chip architecture a step forward by finding a way to refresh the short-lived signals the scheme uses to represent the 1s and 0s of digital information.

The architecture promises to provide computer circuits that are faster and use much less power than today's transistor-based chips.

The researchers' quantum dot cellular automata scheme carries out the logic of computing using the positions of individual electrons trapped in quantum dots rather than large numbers of electrons flowing through transistors. The drawback to having no current flow through a device, however, is current cannot be used to boost signal strength.

Key to the plan was figuring out a new way to boost fading signals.

Like conventional chips, the researchers' device must refresh its signals because electronic circuits are not 100 percent efficient. "Digital signals lose part of their energy as they move along," said Ravi Kummamuru, a researcher at Notre Dame. "Just like a voice signal cannot be heard between two points a mile apart unless it is repeated or amplified every 100 meters... a digital signal has to be amplified at regular intervals along a circuit," he said.

The researchers' instead found a way to use the computer clock signal to restore signal strength, said Kummamuru. A computer clock sends a signal through all of a computer's circuits to synchronize them, which makes it possible to construct complicated, sequential logic operations using combinations of relatively simple circuits.

Under the researchers' architecture, electrons can be trapped in quantum dots, individual molecules, or metal tunnel junctions. Quantum dots are microscopic specks of semiconductor material, and metal tunnel junctions are circuits that contain infinitesimal gaps.

The researchers tested their architecture using tunnel junctions with aluminum islands that trap electrons. Each island was about 50 nanometers wide, or the width of 500 hydrogen atoms, and several thousand nanometers long.

The researchers arranged four islands into a square and used the resulting cell to trap a pair of electrons. The Coulomb force, which causes particles that have the same type of charges to repel each other, forced the negatively-charged electrons into opposite corners of the square. The two possible opposite corner positions can represent the binary numbers 0 and 1.

Quantum tunneling allows the electrons to switch corners, changing the state of a cell from 0 to 1 or 1 to 0. Tunneling is a weird quantum phenomenon in which an electron disappears and reappears on the other side of an otherwise impenetrable barrier.

The Coulomb force also causes a cell to affect the state of the cell next to it. This allows a bit of information to be transmitted through a line of cells. The researchers placed an additional island between each pair of islands in the cell to latch each bit. When an electron is trapped in a middle island, it blocks the electrons in the corner islands from switching corners, said Kummamuru.

The clock signal triggers the latch, and the latch keeps the electrons from tunneling for longer than a clock cycle, meaning the bits of information survive long enough to be affected by the next clock cycle.

The researchers measured the energy flow through a latch, and found that the power gain was enough to trigger the next latch in turn, and thus restore the entire system's logic, according to Kummamuru. "In quantum dot cellular automata devices, which use neither transistors nor supply lines, power gain can still be achieved by using power from the clock signal," he said.

In previous work, the researchers figured out how to use various arrangements of cells to make digital circuits that carry out the basic logic of computing. Quantum dot cellular automata logic has counterparts for all of the basic digital logic elements available in traditional transistor-based systems, Kummamuru said.

Circuits formed by tunnel junctions, quantum dots or molecules can be considerably smaller than circuits formed by the transistors in today's chips, and the smaller they are, the more efficient they are; the opposite holds for conventional transistors, said Kummamuru. "Quantum... devices will improve as they become smaller," he said.

The scheme faces several challenges that must be overcome before practical devices are possible, said John C. Lusth, an associate professor of computer science at the University of Arkansas. "While I have no doubt [the scheme] will work as the Notre Dame researchers envisioned, I do wonder about the utility of this approach," he said.

The major problem with using metal tunnel junctions is "there are wires running to every cell, so [the scheme] is size-limited just like conventional transistor logic," said Lusth.

Compounding the problem is that the researchers' device requires extremely low temperatures. Although the researchers "talk about molecular implementations [that] could possibly compute at room temperatures... the clocking logic as currently envisioned cannot be made that small without deleterious quantum-mechanical effects," he said.

It will be 10 to 20 years before practical devices can be made using the scheme, said Kummamuru.

Kummamuru's research colleagues were John Timler, Geza Toth, Craig Lent, Rajagopal Romasubramaniam, Alexei Orlov, Gary Bernstein and Gregory Snider. The research appeared in the August 12, 2002 issue of *Applied Physics Letters*. The research was funded by the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research (ONR), the W. M. Keck Foundation, the National Science Foundation (NSF) and Intel Corporation.

Timeline: 10-20 years
Funding: Government; Private; Corporate
TRN Categories: Integrated Circuits; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Power gain in a quantum-dot cellular automata latch," *Applied Physics Letters*, August 12, 2002

Quantum Dot Logic Advances

By Eric Smalley, Technology Research News
October 11, 2000

Efforts to make computers using quantum dots, which are microscopic specks of material that behave like atoms, have taken two steps forward with the development of a switch that needs no leads to the external environment and a clocking function that controls the switch.

In theory, quantum dots can be grouped into cells that in turn can be combined to form the logic gates, memory units and wires that are the building blocks of computers. Computer components based on these cells would be much faster and smaller and would use less power than those made with today's semiconductor technology.

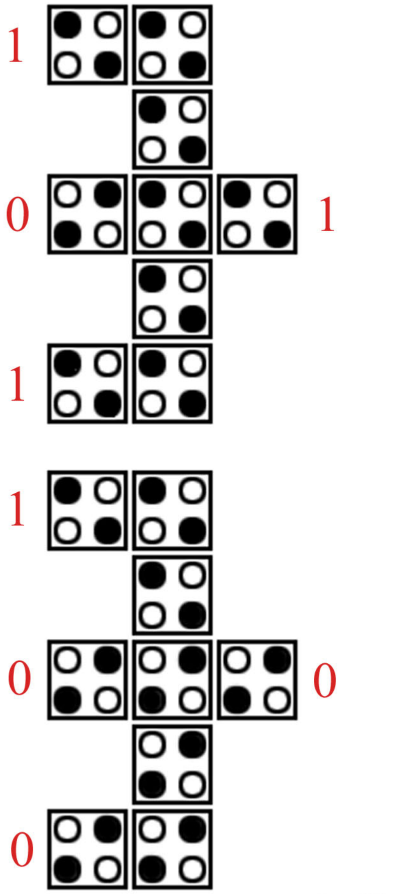
Researchers at Notre Dame are developing Quantum-dot Cellular Automata (QCA), a computer architecture based on quantum dot cells. They have demonstrated QCA cells that are completely isolated from the environment and the clocking function that could move and store bits in a QCA-based computer. The research shows how to make QCA-based computers should researchers learn how to make quantum dots precisely enough to build the devices.

The cells developed at Notre Dame use a stand-in for quantum dots. "These are actually metallic islands that are playing the role of quantum dots," said Gregory L. Snider, an associate professor of electrical engineering at Notre Dame and one of the principal researchers on the QCA project. "They have the same basic properties [required for QCA] that quantum dots have."

A cell based on four metallic islands is 3,000 to 4,000 nanometers across. In theory, a cell based on quantum dots would be less than 100 nanometers across.

The Notre Dame researchers have succeeded in building a QCA cell out of four metallic islands that are physically isolated from each other and the environment, said Ravi K. Kummamuru, a graduate student at Notre Dame and researcher on the project. Previous QCA cells included electrical leads used to control the gates on the islands, he said.

"This is as close as it gets to the ideal QCA cell," he said. "The electron occupancy of the cell is controlled by gates that are capacitively coupled." This means that the gate on an island is controlled by a nearby, but physically separate object with an electrical charge. In the case of a QCA cell, the nearby object is a gate on an adjacent island.



Source: TRN

This diagram shows a pair of gates made up of cells of four quantum dots each. The solid dots contain electrons while the white dots do not. Because electrons repel each other, they can't exist in adjacent dots. The position of the electrons in the gates' middle cell is determined by a majority of the three surrounding cells, so a majority of inputs on the left deterines the output on the right. All of the logic gates used in binary computing can be configured from combinations of these majority gates.

When the gates are open, electrons are free to jump across to adjacent islands. The four islands in the leadless QCA cell are arranged in a square. When two of the islands contain an electron, the electrons move to diagonally opposite islands because electrons in neighboring islands repel each other. If a gate opens, allowing an electron to move to a neighboring island, the other electron in the cell moves to the island in the opposite corner.

This configuration of four metallic islands has two possible arrangements of two islands containing electrons and two remaining empty. Those two states can serve as the ones and zeros of binary computing, forming a switch.

The movement of electrons within a cell can also trigger movement of electrons in adjacent cells, allowing bits to be transferred across cells.

"You have a line of these cells and you give an input to the first cell, which causes it to switch in one direction. That switching, because of the coupling between each cell, propagates along the QCA line," said Kummamuru.

Moving bits around a computer also requires a clocking function so components can be synchronized. The Notre Dame researchers have done this by adding two clocking islands to the four data islands. They have fashioned a prototype half cell of three islands to demonstrate the concept.

"The middle [island] is used to control the flow of electrons from the top [island] to the bottom [island]," said Kummamuru. "A clocking signal is applied to the center [island], so you can control the flow using a clock. By making it controllable by a clock, it's basically possible to pipeline the QCA architecture and make digital logic possible."

The clocking function also serves to lock cells, making QCA memory possible, said Snider.

QCA-based computing "is an extremely challenging thing to implement. It's very difficult experimentally to actually pull this off," said Eric Snow, research physicist and head of the nanostructures section of the Electronic Science and Technology Division at the Naval Research Laboratory.

One of the biggest challenges facing anyone seeking to make QCA-based computers is being able to produce quantum dots precisely enough and consistently enough to make QCA cells on demand. Researchers at Notre Dame and elsewhere are working on molecular implementations of quantum dots, Snow said. That would mean using chemistry techniques, which are potentially faster, cheaper and more consistent than the semiconductor techniques used today.

"Given some revolution happens [in quantum dot fabrication], you want to form the foundations for [QCA] computing," said Snow. "You have to put the research in first to see if it's even worth the effort to go in that direction." The Notre Dame researchers have put "heroic efforts into those steps," he added.

Useful devices based on the QCA architecture are probably 15 years away, said Snider.

Snider and Kummamuru's colleagues on the research were Islamshah Amlani, Alexei O. Orlov, Gary H. Bernstein, Craig Lent, Rajagopal Ramasubramaniam and Geza Toth. They published their work on leadless quantum-dot cellular automata cells in the July 31, 2000 issue and their work on clocked QCA in the July 10, 2000 issue of the journal *Applied Physics Letters*.

The QCA research was funded by the Defense Advanced Research Projects Agency, the National Science Foundation and the Office of Naval Research.

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switching in quantum-dot cellular automata" *Applied Physics Letters* July 10, 2000

Electron Waves Compute

By Eric Smalley, Technology Research News
April 3/10, 2002

Give an electron two paths to get to one location and it will usually take both. This fact of quantum physics plays a leading role in a computer architecture that could replace today's chip technology when it reaches its limits in a decade or so.

According to the laws of quantum physics, electrons are waves as well as particles. Like ocean waves, where two crests meet they reinforce each other and where a crest and trough meet they cancel each other out. Researchers at University of Missouri at Rolla have devised a scheme for using electron wave interference to represent the ones and zeros of digital computing.

Traditional electronic computers use combinations of transistors, which are tiny electronic switches, as the logic units that perform the binary arithmetic at the heart of digital computing. Electron wave computers would use networks of microscopic wire rings that form the two paths for the electron waves to follow, said Cheng-Hsiao Wu, a professor of electrical and computer engineering at the University of Missouri at Rolla.

"You do not need transistors to control the flow of charge if all the devices involved are very small and at low temperature," said Wu.

The researchers' proposal involves using modified forms of Aharonov-Bohm rings, which are used in basic physics research, to form the logic gates of computers. Aharonov-Bohm rings are circles of extremely thin wire and are commonly made several times smaller than a red blood cell. Due to their wave nature, electrons entering the Aharonov-Bohm rings travel in both directions at once, meeting—and reinforcing each other—at the other end.

Using a magnetic field perpendicular to the ring, researchers can speed up or slow down the electron wave traveling in one side of the ring, throwing the waves in the two sides out of sync and causing the waves to cancel each other out when they meet at the other end. The reinforced waves and the canceled waves could represent the ones and zeros of computing, according to Wu.

Aharonov-Bohm rings have an input and an output terminal. The researchers' scheme calls for making three- and four-terminal Aharonov-Bohm rings. Their work shows that three-terminal rings could be combined to form IF-THEN, XOR, OR, AND and INVERTER logic units. These logic units could, in turn, be combined to form half adders and full adders. A half adder adds two binary numbers but cannot carry, and a full adder includes the carry function.

A single, four-terminal Aharonov-Bohm ring could also be used as a half adder, said Wu. "It replaces eight transistors for the same function." And two connected four-terminal Aharonov-Bohm rings could serve as a full adder. "This replaces about two dozen transistors in traditional microelectronic circuits," he said.

In addition to the potential for making smaller, and therefore faster, computer circuits, electron wave computers could solve certain problems faster than even the fastest ordinary computer by examining all of the possible solutions to a problem at once, according to Wu.

Electron wave interference could be used to make massively parallel processing computers, he said. "Millions of inputs enter a large network [of rings] simultaneously with desirable outputs when the waves arrive at the output terminals. This is similar to optical computing."

Optical computers use light waves that reinforce and cancel each other out. Last year, researchers at the University of Rochester demonstrated an optical computer running a quantum search algorithm.

The electron wave scheme is an idea worth trying, said Ian Walmsley, a professor of experimental physics at the University of Oxford and a professor of optics at the University of Rochester. "The nice thing about electrons is that [their] wavelengths are inherently smaller than optical wavelengths, so the whole machine can be smaller. At present I see the advance as a technical one rather than a fundamental one," he added.

"It's a very neat idea but... completely theoretical," said Mike Lea, a professor of physics at the University of London. "I'd be quite skeptical about claims without at least some analysis of the likely practicalities based on real experiments," he said.

The researchers are working out the physics for larger networks of Aharonov-Bohm rings, said Wu. "I would like to convince experimentalists elsewhere to simply extend the original Aharonov-Bohm effect to three or four terminals. I promise nice results will come out of such a simple extension," he said.

Given that today's semiconductor technology is likely to reach its limits by the year 2015, researchers and engineers should have a good idea of how to build devices smaller than 10 nanometers by then, said Wu. At that point, electron wave computing could be a contender for the next generation computer architecture, he said.

Wu's research colleague was Diwakar Ramamurthy. They published the research in the February 15, 2002 issue of the journal Physical Review B. The research was funded by the university.

Timeline: 13 years
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