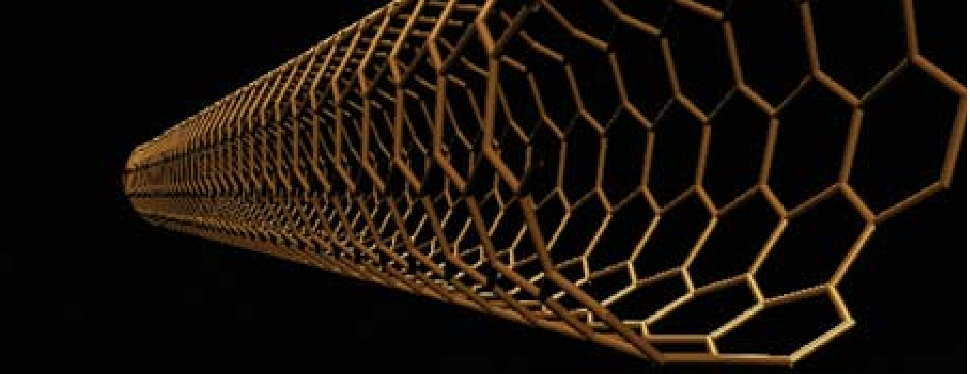
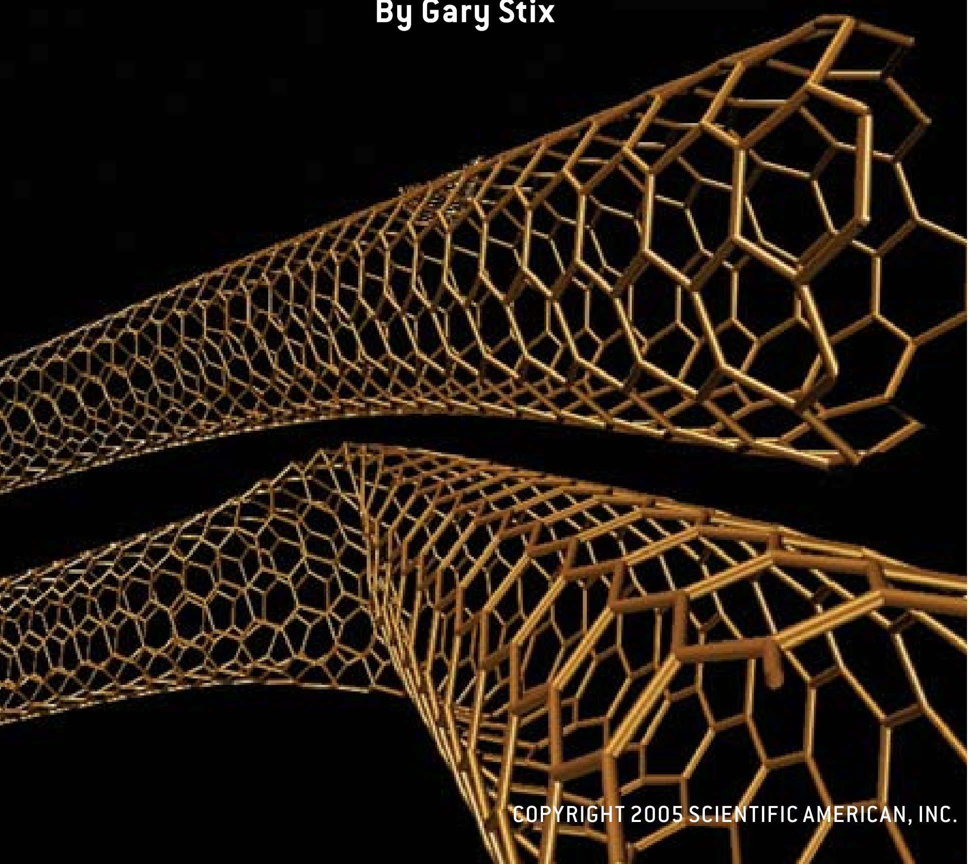


Nanotubes in the Clean Room

Talismans of a thousand graduate projects may soon make their way into electronic memories

By Gary Stix



Charles M. Lieber, a major figure in nanotechnology, asked one of his graduate students in 1998 to undertake the design of a radically new type of computer memory. It would read and write digital bits with memory elements that measured less than 10 billionths of a meter (10 nanometers). Until then, the student, a German native named Thomas Rueckes, had been spending his time in Lieber's laboratory at Harvard University measuring the electrical and material properties of carbon nanotubes. These cylinders, measuring but a nanometer or so in diameter, display a surface of hexagonal carbon rings that give the material the appearance of a honeycomb or chicken wire. Since the discovery of nanotubes in 1991, the scientific community has lauded them for their superlative material and electrical properties.

Lieber wanted to know whether Rueckes could come up with a concept involving nanotubes that could be submitted for funding under a molecular electronics program funded by the Defense Advanced Research Projects Agency. Rueckes pored over books and review articles for a few days, but nothing good suggested itself. One evening he left the chemistry lab and crossed the street to the

cafeteria at the Harvard Science Center. On his pizza run, he passed the Harvard Mark 1, the 55-foot-long monstrosity, a predecessor of modern computers, that had served the U.S. Navy as a calculator for gunnery and ballistic computations until 1959. It now decorated the center's hallway. Back in the lab, he remembered that the Mark 1 operated by moving mechanical relays from one position to another. "That is what flipped a switch in my brain," he remembers. "I could see a picture of how to build a memory."

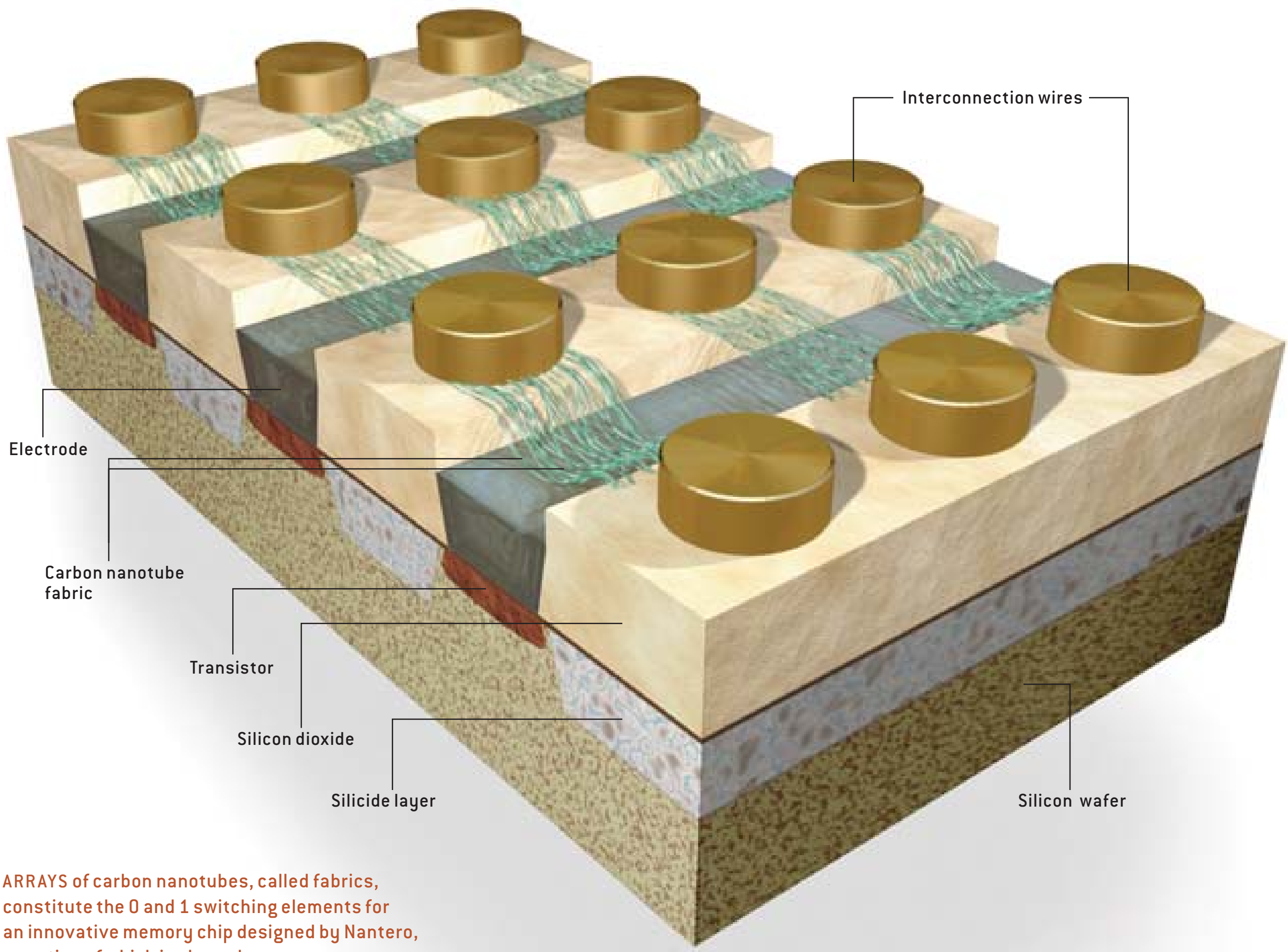
Many researchers were trying to use nanotubes as wires or components in new transistor designs. The Mark 1 inspiration prompted Rueckes to focus instead on their extraordinary tensile strength and resilience. Nanotubes, he imagined, might flex up and down to represent a 0 and a 1 state, like hypershrunken versions of the relays in the Mark 1. "We sat down and worked out a proposal in a couple of days and submitted it to DARPA, and they funded it in one day," Rueckes says.

Until his graduation in 2001, Rueckes continued to develop the concept. As he worked, he realized that nanotubes had more and more to offer. They could, in theory, provide the makings of a universal memory, one that combined the speed of static random-access memory, the low cost of dynamic random-access memory (DRAM), and the nonvolatility (instant-on operation) of flash memory. Its status as *uber*-material would also make it a low consumer of electrical power as well as resistant to potentially damaging heat, cold and magnetism.

When Billionths Meet Trillions

ON PAPER, the design was relatively simple. Nanotubes would serve as individually addressable electromechanical switches arrayed across the surface of a microchip, storing hundreds of gigabits of information, maybe even a terabit. An electric field applied to a nanotube would cause it to flex downward into a depression etched onto the chip's surface, where it would contact another nanotube (in current designs, it touches a metal electrode). Once bent, the nanotubes could remain that way, including when the power was turned off, allowing for nonvolatile operation. Van der Waals forces, which are weak molecular attractions, would hold the switch in place until application of a field of different polarity caused the nanotube to return to its straightened position.

Even before Rueckes had finished at Harvard, he received a visit from an executive at an Internet company who was looking to strike out in a new direction.



ARRAYS of carbon nanotubes, called fabrics, constitute the 0 and 1 switching elements for an innovative memory chip designed by Nantero, a section of which is shown here.

JEAN-FRANCOIS POVEDIN

Greg Schmergel, a Harvard M.B.A. and former management consultant, had come to learn through his experience as an Internet entrepreneur about the fickleness of the new medium and how low the barriers for new entrants were. His company, a successful venture called ExpertCentral.com, which provided professional services references, had experienced these vicissitudes firsthand. It was scooped up by About.com, which, in turn, was bought by Primedia.

Nanotechnology seemed less amenable to dot-com-style feeding frenzies. Most people, even scientists, could not offer a cogent definition, except to point to the science-fiction section at Barnes & Noble. Schmergel did not know all that much about it either, although it did seem as faraway from an Internet company as anything he could imagine. But Schmergel, who was also heir to a long tradition of entrepreneurship (his father started one of the first biotech companies), did know business, whereas Rueckes understood, as well as anyone could, the emerging field of nanotechnology.

So, in 2001, Schmergel and Rueckes, along with Brent M. Segal, another former Harvard chemistry doctoral student, formed Nantero, a name whose genesis again combined the small ("nano") and the large ("tero," a corruption of "tera," or trillions, as in trillions of bits). Lieber himself opted to pursue more advanced projects in his Harvard lab, smart nanowires that would assemble on their own into finished devices and that might use biological or other unorthodox signals for communication among device structures.

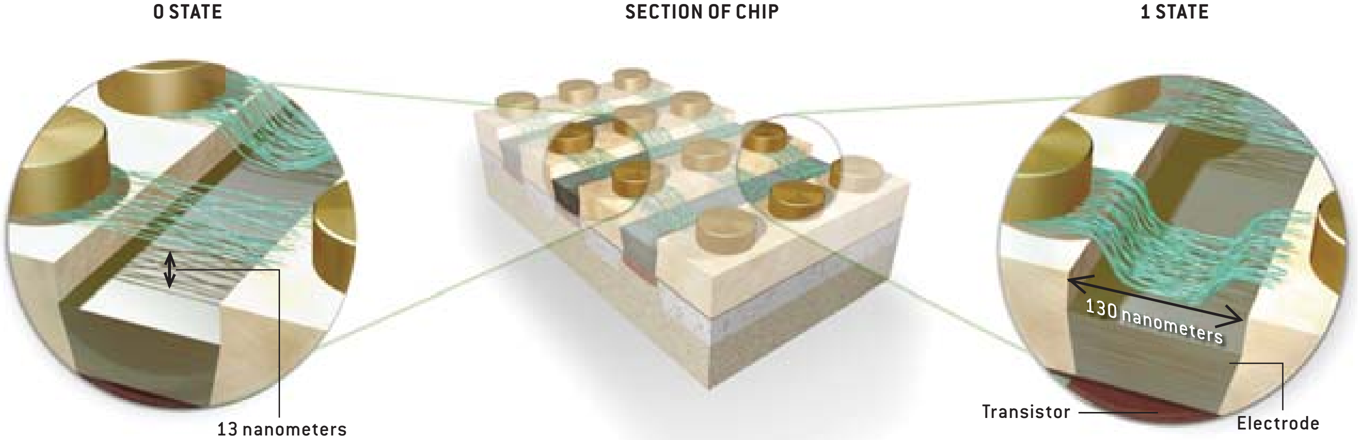
The immediate mandate for Nantero was to move beyond an advanced graduate project to create a device that could be manufactured in a working semiconductor facility. The company set up shop in a Woburn, Mass., industrial park populated largely by biotechnology firms. Schmergel tried to remove as many distractions as possible for his researchers: Nantero is still not listed in the Woburn telephone directory. Early on the team approached a number of big chip manufacturers. Engineers there did not always greet their presentations warmly. Rueckes recalls how one manager sputtered: "We don't want your virus in our plant."

Ironing Things Out

NANOTUBES, purchased from bulk suppliers, are a form of high-tech soot that contains a residue that averages 5 percent iron, a contaminant whose very mention can produce involuntary tremors in managers of multimillion-dollar clean rooms. The Nantero team devoted much of its early development to devising a complex filtration process to reduce the amount of iron to the parts-per-billion level.

Adapting rolled-carbon chicken wire to the standard photolithography and etching process that patterns and removes material to form electrical circuitry proved just as daunting. New chip factories cost more than $2 billion, and notoriously conservative plant managers had no inclination to retool to integrate nanotubes into the standard CMOS (complementary metal oxide semiconductor) manufacturing process. When Nantero started, no good options existed for forming a nanotube on the surface of a wafer (the round silicon disk from which chips are carved) without interfering with adjoining electrical circuitry. Deposition of nanotubes onto the wafer using a gas vapor required temperatures so high that the circuitry already in place would be ruined. Alternatively, coating the wafer with a nanotube-containing solvent by spinning the disk like a phonograph record also had its problems. A suitable solvent, chlorobenzene, was considered excessively toxic and had been banned from chip factories.

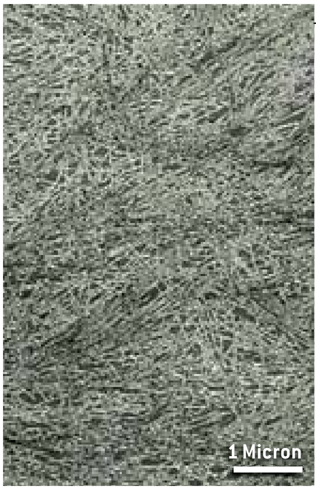
Nantero devised a proprietary solvent suitable for spin coating. The thin film of nanotubes left after the solvent is removed can be subjected to lithography and etching that leaves the surface of the wafer with evenly spaced groupings of nanotubes. On close inspection, the conglomeration of threadlike nanotubes resembles a helter-skelter unwoven fabric. An electric field applied to one of the fabric elements bends it downward until it contacts an electrode, a position that represents a digital 1. ASML, a major semiconductor tool manufacturer, helped to refine this process with Nantero.

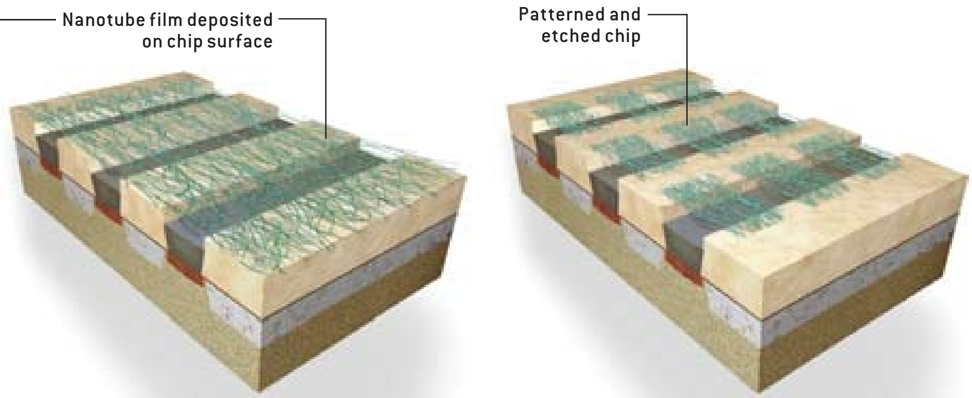


SAGGING AND STRAIGHTENING represent the 1 and 0 states for a random-access memory made up of groupings of nanotubes. In its 0 state, the fabric remains suspended above the electrode (*left*).

When a transistor turns on, the electrode produces an electric field that causes a nanotube fabric to bend and touch an electrode, a configuration that denotes a 1 state (*right*).

JEAN-FRANCOIS POVEDIN





LAYER of nanotubes gets deposited onto a section of the chip's surface (*left* and *center*) before material is removed (*right*) using standard semiconductor lithography and etching. Further processing steps (*not shown*) are needed to complete fabrication of the chip.

NANOTERO (*left*); JEAN-FRANCOIS POVEDIN (*center* and *right*)

When Nantero had gained confidence with the technology, it began a new round of visits to semiconductor manufacturers. In 2003 LSI Logic, a leading maker of customized chips for the telecommunications, storage and consumer electronics industries, agreed to bring the process for making what Nantero calls nanotube random-access memory (NRAM) into its factory in Gresham, Ore. To everyone's surprise, the collaborators had a working prototype within nine months. The project was quickly put on an early-development track, targeting the first commercial production memories for 2006. "I'm still amazed that the darn things work, because I was a little skeptical," says Norm Armour, general manager for the Gresham plant. LSI is interested in pursuing the technology as a replacement for fast-access memory modules (static RAM) embedded on microprocessors that consume an ever larger part of the chip area. A nanotube memory could be faster and much smaller while consuming less power.

In coming months, LSI and Nantero will strive to increase "yield," the ability to make millions of nanotube memories with near-perfect repeatability. To achieve high yields, engineers must attend to a multitude of details. If, for instance, the cavity over which the nanotube is suspended does not form sharp enough edges, it can adversely affect the device's electrical characteristics, changing the voltage at which it turns on and off. "The yield question is a big question, but we don't see anything insurmountable," comments Verne Hornback, LSI's senior project manager on the Nantero collaboration.

Although nanotube memories have intrigued the industry, skepticism remains. "Nantero has a great idea, but I believe it is a long way from having a credible manufacturing process," says G. Dan Hutcheson, who heads the market analysis firm VLSI Research in Santa Clara, Calif. He adds: "I will be very surprised if Nantero can make a scaled-up device that can compete cost-effectively with a DRAM as they claim, because I doubt that their process is scalable and repeatable. So the yields will be low."

A leader in this area of research, IBM has not pursued nanotube memories. The company has decided to focus on using nanotubes to replace a critical component that shuttles electrons from one side of a transistor to another. "We have no problems in finding choices for memory, but we're running out of choices for logic. And nanotubes offer unique properties for logic," observes Phaedon Avouris, a scientist at the IBM Thomas J. Watson Research Center.

Of course, Nantero thinks that the development work with LSI this year will disprove the doomsayers—for instance, the use of nanotube fabrics instead of the individual nanotubes as switching elements, which was an approach employed in the early design at Harvard, mitigates concerns about variability in size among the tubes. And the company has already attracted another partner, BAE Systems, to work on defense and aerospace applications for the radiation-resistant NRAMs. Even if the chips do not meet expectations, Nantero, which has filed for 60 patents and been granted 10 of those applications, will be left with valuable manufacturing know-how that could be licensed to others who want to combine nanotubes with chipmaking.

Just getting nanotubes into a factory at all marks a milestone. "The biggest victory we've had is to bring the process into a standard CMOS facility," LSI's Hornback remarks. A nanotube chip in a cell phone would be sweet vindication for the legions of researchers who have spent the early part of their careers poking and shocking these invisible specks. Until now, virtually the only products that incorporate this material that is stronger than steel and as hard as diamond have been glowing press releases from universities and industry. SA

MORE TO EXPLORE

The Incredible Shrinking Circuit. Charles M. Lieber in *Scientific American,* Vol. 285, No. 3, pages 58–64; September 2001.

Supertubes. Phaedon Avouris in *IEEE Spectrum,* Vol. 41, No. 8, pages 40–45; August 2004.

Information about Nantero and NRAMs can be accessed at **www.nantero.com**