The Coming Chip Revolution
Facing the limits of silicon, scientists are turning to carbon nanotubes

In a dimly lit lab in Yorktown Heights, N.Y., the workbenches are crowded with scanning-tunneling microscopes, atomic force probes, and an assortment of other tools used to render the molecular world visible. There, at IBM's (IBM) Thomas J. Watson Research Center, Phaedon Avouris and his team are using these instruments to conquer the Everest of nanotechnology: They're learning how to weave wisps of carbon, atom by atom, into working transistors.

Avouris' aim is to outrun a ticking clock. Since the dawn of the semiconductor industry a half-century ago, computer companies have depended on chipmakers to keep Moore's Law on track, doubling the speed of their devices every 18 months. The chipmakers achieved this magic by packing transistors more closely together on ever-shrinking flecks of silicon. Tinier transistors run faster. But the chips also run hotter, and they become much more complicated to produce. As chip features shrink from 90 nanometers today toward 20 nm or 10 nm over the next decade, the burdens of heat, cost, and unruly physics could render silicon useless. If the industry doesn't find an alternative, Moore's Law will hit a brick wall.

EFFICIENT REPLACEMENT
The problems are already taking a toll. Today's fastest PC chips run hot enough to cook an egg. If unchecked, the increase in heat is on track to hit metal-melting temperatures by decade's end. That not only wastes power -- as much as half the power consumed by today's fastest processors may be lost as heat -- but can also slow down or even damage a chip. And due to the increasing complexity of the fabrication process, the price tag of a single semiconductor factory, or fab, could hit $10 billion by the decade's end, up from $2 billion today. "Chipmakers have to get away from multibillion-dollar fabs," says Sam Brauer, a principal at Nanotech Plus LLC, a market consultant in Stamford, Conn. "It's their Holy Grail."

At IBM, Infineon (IFX), NEC (NIPNY), and a clutch of startups, the leading candidate to replace silicon is the ethereal carbon nanotube. This tiny molecule -- 100,000 lined up side by side are about as thick as a human hair -- promises to make circuits faster, less power-hungry, and more densely packed than anything possible today. And they could vastly simplify the way chips are made.

Even though such transistors are still in their infancy, says IBM's Avouris, "Carbon nanotubes can get around most of the problems that doom very small silicon devices." In the lab, he has backed this statement up. It took him four years to assemble his current, third-generation prototype of a carbon nanotube transistor, but in the end, the device can carry up to 1,000 times the current of the copper wires used in today's silicon chips, making it vastly more efficient.

The nanotubes themselves are deceptively simple. Joined in superstrong hexagonal bonds, carbon atoms arrange themselves in a cylinder, like a coil of chicken wire. By changing the geometry of the tube's honeycomb of atoms, researchers can tune them to resist or conduct electricity, which is one reason they can carry very high currents while emitting little heat. "Mixing together nanotubes with different electrical properties could simplify the design of future chips," says Paolo A. Gargini, chairman of the International Technology Roadmap for Semiconductors, an industry planning consortium, and Intel Corp.'s (INTC) director of technology strategy. It would eliminate many of the exotic chemicals and processes now used to make chips.

The virtues of nanotubes go beyond electricity. In addition to being excellent conductors of heat, the tubes are 10 times stronger than steel and are resistant to radiation. This matters because as chips get smaller, they are becoming more vulnerable to damage from high-energy solar particles. So, long before they replace transistors as the brains of chips, says Craig Sander, Advanced Micro Devices' (AMD) vice-president for technical development, carbon nanotubes are likely to be mixed in as part of the chip's structural layer.

TRICKY PHYSICS
For all their promise, nanotubes face huge challenges going from lab to fab. Current production techniques yield a stew of more than 30 varieties of nanotubes, points out Tim Gierke, a nanotechnology researcher at DuPont (DD). Some players, such as Houston's Carbon Nanotechnologies Inc., are striving to refine their production recipes to make more of the most desirable variety. DuPont, meanwhile, is working on tools to sort tubes by their size and electrical properties.

Even with a reliable supply of tubes, scaling up production to supply a vast global industry will take years. Researchers at both
IBM and Infineon have built nanotube transistors with electrical properties far superior to those of silicon. But today's most powerful processors have a billion transistors each. Scientists have no idea how to match the enormous efficiency of today's manufacturing methods, says Gargini.

What nobody disputes is that the existing recipe for making silicon chips is already running into trouble. Circuits work a little like garden hoses: When you make a hose narrower, you have to increase the water pressure to get the same volume through it. Likewise, chipmakers have had to boost the voltage on the chips so that more current can pass through smaller circuit lines. At the same time, chips are getting "leakier," like a hose riddled with pinpricks. There are simply fewer atoms in the chips' insulation layers to keep electrons from tunneling through.

Other problems are surfacing, too. Once-inconsequential variations among the millions of transistors on a chip begin to matter at smaller dimensions. On a Pentium 3, circa 2003, with circuit lines a generous 180 nanometers wide, a 20-nm defect was nothing to worry about. But at today's 90-nm standard, such a flaw can render a transistor useless. "The hell of nanoscale physics" is how Hugo De Man, a senior researcher at Belgium's Interuniversity Microelectronics Center, describes the fast-multiplying challenges chipmakers face.

What's more, the tricky physics is driving up the cost for next-generation plants. Infineon Technologies' new memory-chip factory in Richmond, Va., showcases the staggering complexity -- and expense -- necessary to stay competitive. Roughly four football fields in size, the $2 billion facility is part of an elite club of chip plants that, on a per-acre basis, rank among the most costly factories ever built.

Inside this hangar-like factory, machines build machines. Untouched by human hands for weeks, chips-in-progress pass through hundreds of processes, moving to and from dozens of million-dollar machines via a pint-size robotic monorail. The chips will travel miles in this plant before emerging, after two to three months of processing, as a commodity RAM chip, ready for your next desktop.

Laborious as this process is, it will be hard to supplant. At the end of the day, chip quality is high. And there are ways to get around heat, such as designing better "architectures" -- the way transistors are organized on the chip. AMD, IBM, Intel, and others are exploring "multicore" processors that multiply the number of brains on a chip from one to two, and in time, to four or more.

Whether nanotube-based chips are 10 years away or 20, experts agree the transition will be incremental. First they expect to see hybrid silicon-nanotube designs -- an approach that suits the industry's titans. With 50 years of experience in silicon, billions invested in R&D, and countless more sunk into silicon-based factory processes, chipmakers prefer enhancements to the current model, not disruptive substitutes. "The shift has to be evolutionary," says George M. Scalise, president of the Semiconductor Industry Assn.

Silicon-carbon hybrids are part of that trend. Nantero Inc., a Woburn (Mass.)-based startup, is working with LSI Logic Corp. (LSI) to make nanotube RAM using existing silicon processes. Nanotube-based memory, says Nantero CEO Greg Schmergel, is as fast and dense as the RAM now used in computers but can maintain data without power, like the more costly flash memory used in digital cameras. "Imagine booting up your PC instantly or replacing your hard drive with much faster RAM," says Schmergel.

Nantero is hoping for a major performance leap, but others are skeptical, noting that it can take 10 years to perfect even small steps forward in existing chip technologies. So for the next big leap, the industry is taking a long running start.

By Adam Aston in New York