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The First Carbon Nanotube Computer

A carbon nanotube computer processor is comparable to a chip from the early 1970s, and may be the first step beyond silicon electronics.

By Katherine Bourzac on September 25, 2013

For the first time, researchers have built a computer whose central processor is based entirely on carbon nanotubes, a form of carbon with remarkable material and electronic properties. The computer is slow and simple, but its creators, a group of Stanford University engineers, say it shows that carbon nanotube electronics are a viable potential replacement for silicon when it reaches its limits in ever-smaller electronic circuits.

The carbon nanotube processor is comparable in capabilities to the Intel 4004, that company’s first microprocessor, which was released in 1971, says Subhasish Mitra, an electrical engineer at Stanford and one of the project’s co-leaders. The computer, described today in the journal *Nature*, runs a simple software instruction set called MIPS. It can switch between multiple tasks (counting and sorting numbers) and keep track of them, and it can fetch data from and send it back to an external memory.

The nanotube processor is made up of 178 transistors, each of which contains carbon nanotubes that are about 10 to 200 nanometer long. The Stanford group says it has made six versions of carbon nanotube computers, including one that can be connected to external hardware – a numerical keypad that can be used to input numbers for addition.

Aaron Franklin, a researcher at the IBM Watson Research Center in Yorktown Heights, New York, says the comparison with the 4004 and other early silicon processors is apt. “This is a terrific demonstration for people in the electronics community who have doubted carbon nanotubes,” he says.

Franklin’s group has demonstrated that individual carbon nanotube transistors – smaller than 10 nanometers – are faster and more energy efficient than those made of any other material, including silicon. Theoretical work has also suggested that a carbon nanotube computer would be an order of magnitude more energy efficient than the best silicon computers. And the nanomaterial’s ability to dissipate heat suggests that carbon nanotube computers might run blisteringly fast without heating up – a problem that sets speed limits on the silicon processors in today’s computers.

Still, some people doubt that carbon nanotubes will replace silicon. Working with carbon nanotubes is a big challenge. They are typically grown in a way that leaves them in a tangled mess, and about a third of the tubes are metallic, rather than semiconducting, which causes short-circuits.

Over the past several years, Mitra has collaborated with Stanford electrical engineer Philip Wong, who has developed ways to sidestep some of the materials challenges that have prevented the creation of complex circuits from carbon nanotubes. Wong developed a method for growing mostly very straight nanotubes on quartz, then transferring them over to a silicon substrate to make the transistors. The Stanford group also covers up the active areas of the transistors with a protective coating, then etches away any exposed nanotubes that have gone astray.

Wong and Mitra also apply a voltage to turn all of the semiconducting nanotubes on a chip to "off." Then they pulse a large current through the chip; the metallic ones heat up, oxidize, and disintegrate. All of these nanotube-specific fixes – and the rest of the manufacturing process – can be done on the standard equipment that's used to make today's silicon chips. In that sense, the process is scalable.

Late last month at Hot Chips, an engineering design conference hosted, coincidentally, at Stanford, the director of the Microsystems Technology Office at DARPA made a stir by discussing the end of silicon electronics. In a keynote, Robert Colwell, former chief architect at Intel, predicted that by as early as 2020, the computing industry will no longer be able to keep making performance and cost improvements by doubling the density of silicon transistors on chips every 18 to 24 months – a feat dubbed Moore's Law after the Intel cofounder Gordon Moore, who first observed the trend.

Mitra and Wong hope their computer shows that carbon nanotubes may be a serious answer to the question of what comes next. So far no emerging technologies come close to touching silicon. Of all the emerging materials and new ideas held up as possible saviors – nanowires, spintronics, graphene, biological computers – no one has made a central processing unit based on any of them, says Mitra. In that context, catching up to silicon's performance circa 1970, though it leaves a lot of work to be done, is exciting.

Victor Zhirnov, a specialist in nanoelectronics at the Semiconductor Research Corporation in Durham, North Carolina, is much more cautiously optimistic. The nanotube processor has 10 million times fewer transistors on it than today's typical microprocessors, runs much more slowly, and operates at five times the voltage, meaning it uses about 25 times as much power, he notes.

Some of the nanotube computer's sluggishness is due to the conditions under which it was built – in an academic lab using what the Stanford group had access to, not an industry-standard factory. The processor is connected to an external hard drive, which serves as the memory, through a large bundle of electrical wires, each of which connects to a large metal pin on top of the nanotube processor. Each of the pins in turn connects to a device on the chip. This messy packaging means the data has to travel longer distances, which cuts into the efficiency of the computer.

With the tools at hand, the Stanford group also can't make transistors smaller than about one micrometer – compare that with Intel's announcement earlier this month that its next line of products will be built on 14-nanometer technology. If, however, the group were to go into a state-of-the-art fab, its manufacturing yields would improve enough to be able to make computers with thousands of smaller transistors, and the computer could run faster.

To reach the superb level of performance theoretically offered by nanotubes, researchers will have to learn how to build complex integrated circuits made up of pristine single nanotube transitors. Franklin says device and materials experts like his group at IBM need to start working in closer collaboration with circuit designers like those at Stanford to make real progress.

“We are well aware that silicon is running out of steam, and within 10 years it’s coming to its end,” says Zhirnov. “If carbon nanotubes are going to become practical, it has to happen quickly.”

Credit: Image by Butch Colyear

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