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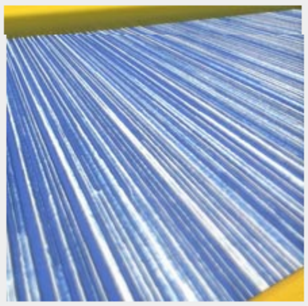
A Breakthrough in Nanotube Transistors

High-current transistors made from perfectly aligned carbon nanotubes show promise for use in flexible and high-speed nanoelectronics.

By Prachi Patel-Predd



Tube transistors: Researchers at the University of Illinois at Urbana Champaign have developed a technique to grow thousands of carbon nanotubes (shown in blue and white in this colorized scanning electron micrograph). The researchers deposit electrodes (shown in gold) on two sides of the nanotube arrays to create transistors that have hundreds of nanotubes bridging the electrodes.
Credit: John Rogers, UIUC

Controlling the growth of carbon nanotubes over large surface areas is essential for making transistors with sufficient current outputs and consistent properties for use in electronic circuits. In a significant advance toward such nanotube-based electronics, researchers at the University of Illinois at Urbana Champaign (UIUC) have grown rows of perfectly aligned carbon nanotubes on quartz crystal and used these arrays to make transistors. The electrodes in these transistors border the nanotube rows so that thousands of nanotubes bridge the electrodes, increasing the current.

In a *Nature Nanotechnology* paper, the researchers, led by John Rogers, a professor of materials science and engineering at UIUC, have demonstrated transistors made with about 2,000 nanotubes, which can carry currents of one ampere--thousands of times more than the current possible with single nanotubes. The researchers have also developed a technique for transferring the nanotube arrays onto any substrate, including silicon, plastic, and glass.

The nanotube transistors could be used in flexible displays and electronic paper. Because carbon nanotubes can carry current at much higher speeds than silicon, the devices could also be used in high-speed radio frequency (RF) communication systems and identification tags. In fact, the research team is

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working with Northrop Grumman to use the technology in RF communication devices, says Rogers.

Until now, making transistors with multiple carbon nanotubes meant depositing electrodes on mesh-like layers of unaligned carbon nanotubes, Rogers says. But since the randomly arranged carbon nanotubes cross one another, at each crossing, flowing charges face a resistance, which reduces the device current. The perfectly aligned array solves this problem because there are "absolutely no tube-tube overlap junctions," Rogers says.

The research team makes the arrays by patterning thin strips of an iron catalyst on quartz crystals and then growing nanometer-wide carbon nanotubes along those strips using conventional carbon vapor deposition. The quartz crystal aligns the nanotubes. Then the researchers can make transistors by depositing source, drain, and gate electrodes using conventional photolithography.

Researchers have not been able to grow well-aligned nanotube arrays until now, according to Robert Hauge, a chemistry professor who studies carbon nanotubes at Rice University. Indeed, "alignment is no longer a showstopper," says Ali Javey, an assistant professor of electrical engineering and computer sciences at the University of California, Berkeley.

Making a well-ordered array in which parallel nanotubes are connected between the source and drain electrodes is a big achievement, says Richard Martel, a chemistry professor at the University of Montreal. The new work allows a true comparison between nanotube transistors and silicon transistors because an array of nanotubes gives a planar structure similar to silicon devices, he says. "They did exactly what needed to be done, and it's a significant

The researchers made and tested hundreds of nanotube transistors, and they found that the devices have consistent electrical properties, even though the property of each nanotube in a device may vary slightly. "There's such a large number of tubes operational in each device that there's a statistical averaging effect," Rogers says.

Moreover, the nanotubes' properties do not change even if they are transferred to plastics or other substrates. "[The] tubes are physically lifted off quartz and then printed down on target substrate so that it doesn't disturb the position and orientation of the nanotubes," Rogers says. Because of this transfer process, he says that the arrays could be integrated with silicon fabrication to make circuits with interconnected nanotube and silicon devices--the nanotube devices could handle the circuit's high-speed operations. To make such a chip, one would only need to transfer the nanotube arrays to the silicon wafer at the beginning of fabrication. Once that is done, one could add silicon devices. "You don't even think about them as tubes," says Roger. "In effect, it's a thin-film uniform substrate, and you just do your processing."

For now, the new transistors will be useful for larger electronics circuits such as those in flexible displays and RF chips, but to be used in high-performance electronics like computer chips, the devices need a much better structure and geometry, Javey says. For instance, the devices would need to be much smaller than they are now: the transistors are currently tens of micrometers long and wide.

To make smaller devices, the UIUC team is working on making the arrays denser. Right now, the distance between adjacent tubes is 100 nanometers, but theoretically, this separation could go down to only one nanometer without affecting electrical properties, Martel says.

Another key area that needs work is finding an effective way to make devices with only semiconducting nanotubes, Rogers says. Typically, a third of the nanotubes in any grown batch are metallic, which causes a small current to flow through a transistor even when it is turned off. The researchers use a common trick to get rid of metallic tubes: turn a transistor off and apply a high voltage that blows out the metallic tubes. But to make good-quality transistors on a larger scale, they would need to find a better way to get rid of the metallic tubes or selectively grow semiconducting tubes. That, according to Javey, is the "last big key" for making nanotube electronics.

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