Flexible Transistors with High Carrier Mobilities Made from Carbon Nanotubes

Organic-based electronics are of great interest as a replacement for inorganic semiconductor devices, as the former are inexpensive, lightweight, and flexible, allowing the development of large flexible displays and electronic paper. However, progress in integrated organic-based electronic devices has been slow due to the low charge-carrier mobilities of these materials, which typically range from ~0.1 cm^2/V s—for example, poly(3-hexylthiophene)—to a maximum of ~2 cm^2/V s for the best *p*-type crystalline organic semiconductors, with *n*-type carrier mobilities even lower. Carbon nanotubes show promise in overcoming these limitations because their carrier mobility exceeds even common semiconductor materials. Not only do carbon nanotubes exhibit very high strength, but their flexibility makes them a promising material for the development of large-scale flexible electronics. A team of researchers from Nanomix Inc. in Emeryville, Calif., recently demonstrated carbon nanotube-based *p*-type transistor networks supported on a flexible polymer substrate with an order of magnitude increase in hole-carrier mobility.

As reported in the October issue of *Nano Letters*, K. Bradley, J.-C.P. Gabriel, and G. Grüner of Nanomix manufactured and tested carbon nanotube network transistors on flexible polymer substrates. These polymer-supported networks show high durability during repeated bending and exhibit a hole-carrier mobility of 12 cm^2/V s. The researchers used chemical vapor deposition to grow the carbon nanotube networks on 200-nm-thick silicon oxide layers on a Si substrate that consist of randomly oriented individual nanotubes rather than bundles. Using conventional lithography, the researchers patterned Ti/Au source/drain contacts onto the nanotube networks (3.5 nm Ti followed by 50 nm Au; 200 μm pads separated by 50 μm gaps), resulting in a field-effect transistor network with on/off ratios as high as 10^4. The scientists transferred the semiconducting networks to a flexible polymer substrate by spin-coating a 15 μm polyimide film as the polymer support onto the silicon substrate, followed by a HF etch step to remove the SiO_2 layer to induce device lift-off.

The devices were tested for their performance by placing the polyimide films on a metal chuck, which served as the gate electrode. The resulting device transfer characteristics exhibited large modulations in conductance for voltages of less than 100 V, confirming that the polymer-supported networks behave as field-effect transistors. For a dielectric film as thick as 15 μm, these switching voltages are remarkably low, according to the researchers. The research team said that the low switching voltage is due to the high carrier mobility of the carbon nanotube network, with a measured hole mobility of 12 cm^2/V s. This mobility is an order of magnitude improvement over the best currently used organic materials. The flexible network devices are remarkably resilient: A 60° bending produces only a 12% decrease in conductance with full recovery over 12 bending cycles performed, despite the presence of multiple nanotube–nanotube junctions. The fabricated polymer-supported network transistors exhibit electronic properties that are similar to those of more conventional, silicon-supported carbon nanotube devices; they are flexible and could be made inexpensively.

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Fluorescence from Individual Single-Walled Carbon Nanotubes Is Not Intermittent

Potential photonic applications of single-walled carbon nanotubes (SWNTs) include nanometer-scaled integrated electroluminescent devices. Development of nanodevices, by their very nature, would benefit from the determination of specific optical properties of individual molecules, such as the true spectral linewidth. Until now, only ensemble-averaged spectra of SWNTs, in which spectral details are obscured, have been reported. However, a research team has reported fluorescence spectra from individual SWNTs. Their findings were published in the September 5 issue of *Science*.

University of Rochester and Universität Siegen researcher A. Hartschuh, together with a team of researchers, isolated individual nanotubes by spin-coating a SWNT suspension onto a glass coverslip. Atomic force microscopy showed that short SWNTs, with lengths of 200–300 nm, predominated. A density of about 10–20 Raman-active nanotubes per 100 μm^2 was determined with confocal Raman imaging. Laser excitation at 633 nm ensured that Raman signals (between 633 nm and 770 nm) were isolated from the fluorescence signals above 850 nm.

Using simultaneous resonance Raman and fluorescence measurements, the researchers found that individual nanotubes