MATERIALS SCIENCE

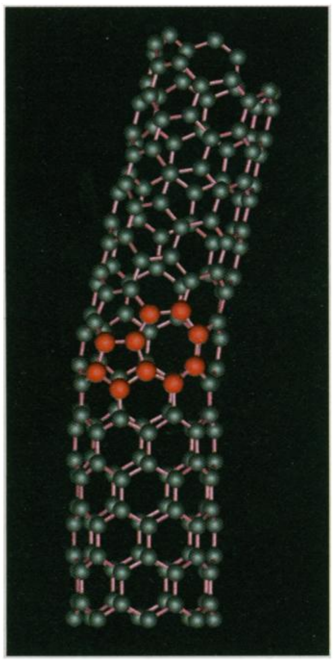
Mixing Nanotube Structures To Make a Tiny Switch

Electronic switches once consisted of elaborate constructions of metal and glass, then of finely etched bits of silicon. Now some researchers are dreaming of switches made of nothing but tiny whiskers of carbon—so-called nanotubes, hollow cylinders of carbon atoms typically no more than 15 nanometers in diameter. Two research teams have developed a way—in theory—to make an all-carbon nanotube that behaves like a semiconductor at one end and a metal at the other. The intersection in the middle forms a gatelike junction that controls the flow of electrons. In the macroworld, such gates, known as heterojunctions, form the basis for transistors and a host of other electronic devices.

A team from the University of California, Berkeley, building on the original presentation of their work last August at a conference in Paris, reports in the 5 February issue of *Physical Review Letters* that they've created a computer model of a nanotube in which the carbon atoms in one half are configured so that electrons can move about easily at a continuous range of energy levels, as in a metal. In the other half, a different atomic pattern forces electrons to reside at distinct, separate energy levels, like a semiconductor. The team, led by physicists Marvin Cohen and Steven Louie, reports that at this particular junction, formed by a deliberate defect in the tube, higher energy electrons from the semiconductor can flow "downhill" to the metal, but they can't travel the other way without an extra electrical shove. A group at the University of Namur in Belgium—led by Philippe Lambin—reported a similar heterojunction model last October.

Moreover, these hybrid tubes may be more than theory. Other groups have recently logged experimental sightings of nanotubes with the unusual shape—a kink at the junction—predicted for the hybrids. These tubes, however, are thicker than those described in the Berkeley model, and that thickness may hold defects that limit the tubes' usefulness; moreover, no one has yet demonstrated any of the tubes to have the predicted electrical function.

Still, Charles Martin, a nanotube expert at Colorado State University in Fort Collins, calls the new work "very interesting," because "heterojunctions are the basis of the semiconductor industry." If nanotube heterojunctions can move from model to reality, say Martin and others, maybe nanotube electronics could make that move as well. And that would be a huge boon, says Cohen, "because nanotubes are about as small as you're going to be able to go in terms of electronics."



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Joint effort. Model nanotube is made from two different patterns of carbon hexagons, joined together by a five- and seven-member ring *(red)*; the junction controls electron flow.

Regular carbon nanotubes are made from a rolled sheet made of six-carbon rings linked in an arrangement like chicken wire. If the sheet is rolled evenly, so that the rows of carbon hexagons circle around the tube to form a band, quantum mechanical principles can restrict the energies of the electrons, explains Cohen, forcing them to occupy separate energy levels, like electrons in a semiconductor.

But if the two ends of each band are offset from one another when the sheet is rolled up, the carbon hexagons spiral up the tube instead of forming complete circles. This alters the quantum mechanical restrictions and can allow the electrons to exist at any one of a continuous range of energy levels, as in a metal.

The trick is to make one tube with both characteristics: bands at one end, for instance, and spirals at the other. Simply stacking a banded tube directly atop a spiraled one doesn't work, however. The lattices of their carbon atoms don't quite match up, leaving a gap. But Cohen and Louie found that most of the gap could be eliminated if the two halves were pressed together at an angle, somewhat like a bent knee. The small remaining hole, they found, could be filled with a pair of defects: a five-carbon ring next to a seven-carbon ring. These defects sit adjacent to one another, creating a small tab that sits above the top band of hexagons and precisely fills in the gap (see diagram). Although multiple defects are usually signs of instability in a nanotube, this single flaw, says Louie, is "the glue that holds the two halves together." At the junction, the energy mismatch of electrons in different halves means the charged particles only flow in one direction.

Lambin and his colleagues, reporting in the 20 October 1995 issue of *Chemical Physics Letters*, found that when they used a different combination of carbon lattice structures in their model, they had to position the five-membered ring and the seven-membered ring defects on opposite sides of the tube. This closed the gaps between the halves of the tube and created the heterojunction.

Whether such hybrid nanotubes actually exist remains an open question. Two other research groups (one at Berkeley, and one at the Bulgarian Acadamy of Sciences in Sofia) have spotted nanotubes with the type of bend predicted by the Berkeley group. These tubes, however, aren't exactly like Cohen and Louie's model hybrids, which are just a single atomic layer thick. Instead, the hybrids discovered thus far are made up of as many as 20 atomic layers, and the distinction could be vital. Multiwalled tubes can possess a variety of defects, which can interfere with their electronic properties in unpredictable ways, rendering them useless as electronic components. Single-walled tubes, on the other hand, are free of defects—except for the crucial one designed in by the models.

And other physicists think that fabricating single-walled hybrids is going to be tough. "It's a mystery how we're going to make them," because the high temperatures of current single-walled nanotube synthesis techniques destroy abnormal carbon rings before they can be incorporated into a tube, says Richard Smalley, a physicist and nanotube expert at Rice University in Houston. Even if the tubes could be made, researchers would then have to attach wires to each end and see if they conduct electricity as predicted. And this has yet to be accomplished for any single-walled nanotube. "Ultimately," says Charles Lieber, a professor of chemistry at Harvard University in Cambridge, Massachusetts, "one has to back up theoretical calculations with something that shows there is some reality to them."

Nanotube models have predicted reality before, of course. Last year, Berkeley researchers discovered boron-nitride nanotubes, first predicted by Cohen and Louie in 1994. As for the new hybrids, Cohen admits that "we can't make them on demand." But by lowering the synthesis temperature, he says, experimentalists may be able to preserve the odd rings long enough for them to create junctions.

–Robert F. Service