tors. That means that, like silicon, they do not pass current easily without an additional boost of energy. A burst of light or a voltage can knock electrons from valence states into conducting states where they can move about freely. The amount of energy needed depends on the separation between the two levels and is the so-called band gap of a semiconductor. It is semiconductors' band gaps that make them so useful in circuits, and by having a library of materials with different band gaps, engineers have been able to produce the vast array of electronic devices available today.

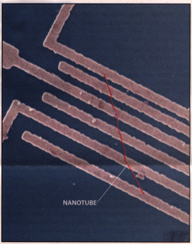
Carbon nanotubes don't all have the same band gap, because for every circumferences there is a unique set of allowed valences and conduction states. The smallest-diameter nanotubes have very few states that are spaced far apart in energy. As nanotube diameters increase, more and more states are allowed and the spacing between them shrinks. In this way, different-size nanotubes can have band gaps as low as zero (like a metal), as high as the band gap of silicon, and almost anywhere in between. No other known material can be so easily tuned. Unfortunately, the growth of nanotubes currently gives a jumble of different geometries, and researchers are seeking improvements so that specific types of nanotubes can be guaranteed.

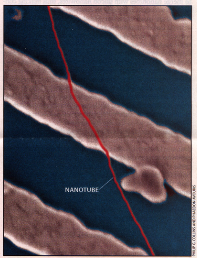
Fat multiwalled nanotubes may have even more complex behavior, because each layer in the tube has a slightly different geometry. If we could tailor their composition individually, we might one day make multiwalled tubes that are self-insulating or that carry multiple signals at once, like nanoscopic coaxial cables. Our understanding and control of nanotube growth still falls far short of these goals, but by incorporating nanotubes into working circuits, we have at least begun to unravel their basic properties.

Nanocircuits

Several research groups, including our own, have successfully built working electronic devices out of carbon nanotubes. Our field-effect transistors (FETs) use single semiconducting nanotubes between two metal electrodes as a channel through which electrons flow [*see right illustration on page 63*]. The current flowing in this channel can be switched on or off by applying voltages to a nearby third electrode. The nanotube-based devices operate at room temperature with electrical characteristics remarkably similar to off-the-shelf silicon devices. We and others have found, for example, that the gate electrode can change the conductivity of the nanotube channel in an FET by a factor of one million or more, comparable to silicon FETs. Because of its tiny size, however, the nanotube FET should switch reliably using much less power than a silicon-based device. Theorists predict that a truly nanoscale switch could run at clock speeds of one terahertz or more—1,000 times as fast as processors available today.

The fact that nanotubes come with a variety of band gaps and conductivities raises many intriguing possibilities for additional nanodevices. For example, our team and others have recently measured joined metallic and semiconducting nanotubes and shown that such junctions behave as diodes, permitting electricity to flow in only one direction. Theoretically, combinations of nanotubes with different band gaps could behave like light-emitting diodes and perhaps even nanoscopic lasers. It is now feasible to build a nanocircuit that has wires, switches and memory elements made entirely from





PHILIP G. COLLINS AND PHAEDON AVOURIS

AS ULTRATHIN WIRES, carbon nanotubes could free up space in microchips for more devices, as well as solving heat and stability problems. At a little over a nanometer in diameter, this single-walled nanotube makes lines drawn by state-of-the-art photolithography look huge in comparison.