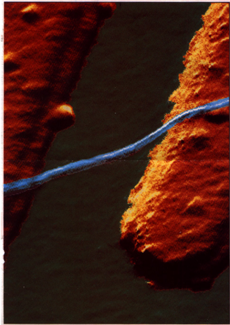
that wires and functional devices tens of nanometers or smaller in size could be made from nanotubes and incorporated into electronic circuits that work far faster and on much less power than those existing today.

The first carbon nanotubes that Iijima observed back in 1991 were so-called multiwalled tubes: each contained a number of hollow cylinders of carbon atoms nested inside one another like Russian dolls. Two years later Iijima and Donald Bethune of IBM independently created single-walled nanotubes that were made of just one layer of carbon atoms. Both kinds of tubes are made in similar ways, and they have many similar properties—the most obvious being that they are exceedingly narrow and long. The single-walled variety, for example, is about one nanometer in diameter but can run thousands of nanometers in length.

What makes these tubes so stable is the strength with which carbon atoms bond to one another, which is also what makes diamond so hard. In diamond the carbon atoms link into four-sided tetrahedra, but in nanotubes the atoms arrange themselves in hexagonal rings like chicken wire. One sees the same pattern in graphite, and in fact a nanotube looks like a sheet (or several stacked sheets) of graphite rolled into a seamless cylinder. It is not known for certain how the atoms actually condense into tubes [see "Zap, Bake or Blast," on page 67], but it appears that they may grow by adding atoms to their ends, much as a knitter adds stitches to a sweater sleeve.



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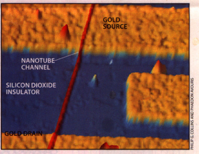
Tubes with a Twist

However they form, the composition and geometry of carbon nanotubes engender a unique electronic complexity. That is in part simply the result of size, because quantum physics governs at the nanometer scale. But graphite itself is a very unusual material. Whereas most electrical conductors can be classified as either metals or semiconductors, graphite is one of the rare materials known as a semimetal, delicately balanced in the transitional zone between the two. By combining graphite's semimetallic properties with the quantum rules of energy levels and electron waves, carbon nanotubes emerge as truly exotic conductors.



PHILIP G. COLLINS AND PHAEDON AVOURIS

MICROCHIPS OF THE FUTURE will require smaller wires and transistors than photolithography can produce today. Electrically conductive macromolecules of carbon that self-assemble into tubes (*top left*) are being tested as ultrafine wires (*left*) and as channels in experimental field-effect transistors (*above*).

For example, one rule of the quantum world is that electrons behave like waves as well as particles, and electron waves can reinforce or cancel one another. As a consequence, an electron spreading around a nanotube's circumference can completely cancel itself out; thus, only electrons with just the right wavelength remain. Out of all the possible electron wavelengths, or quantum states, available in a flat graphite sheet, only a tiny subset is allowed when we roll that sheet into a nanotube. That subset depends on the circumference of the nanotube, as well as whether the nanotube twists like a barbershop pole.

Slicing a few electron states from a simple metal or semiconductor won't produce many surprises, but semimetals are much more sensitive materials, and that is where carbon nanotubes become interesting. In a graphite sheet, one particular electron state (which physicists call the Fermi point) gives graphite almost all of its conductivity; none of the electrons in other states are free to move about. Only one third of all carbon nanotubes combine the right diameter and degree of twist to include this special Fermi point in their subset of allowed states. These nanotubes are truly metallic nanowires.

The remaining two thirds of nanotubes are semiconduc-