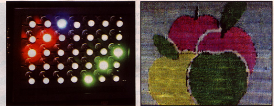
nanotubes and other molecules. This kind of engineering on a molecular scale may eventually yield not only tiny versions of conventional devices but also new ones that exploit quantum effects.

We should emphasize, however, that so far our circuits have all been made one at a time and with great effort. The exact recipe for attaching a nanotube to metal electrodes varies among different research groups, but it requires combining traditional lithography for the electrodes and higher-resolution tools such as atomic force microscopes to locate and even position the nanotubes. This is obviously a long way from the massively parallel, complex and automated production of microchips from silicon on which the computer industry is built.



FIRST ELECTRONIC DEVICES to incorporate nanotubes include vacuum-tube lighting elements (*left*) and a full-color flat-panel display (*right*). Both products make use of nanotubes' ability to emit electrons at relatively low voltages without burning out, which translates into more efficient use of power and possibly greater durability.

ISE ELECTRONICS (*left*); SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY AND SAMSUNG SDI (*right*)

Before we can think about making more complex, nanotube-based circuitry, we must find ways to grow the nanotubes in specific locations, orientations, shapes and sizes. Scientists at Stanford University and elsewhere have demonstrated that by placing spots of nickel, iron or some other catalyst on a substrate, they can get nanotubes to grow where they want. A group at Harvard University has found a way to merge nanotubes with silicon nanowires, thus making connections to circuits fabricated by conventional means.

These are small steps, but already they raise the possibility of using carbon nanotubes as both the transistors and the interconnecting wires in microchip circuits. Such wires are currently about 250 nanometers in width and are made of metal. Engineers would like to make them much smaller, because then they could pack more devices into the same area. Two major problems have so far thwarted attempts to shrink metal wires further. First, there is as yet no good way to remove the heat produced by the devices, so packing them in more tightly will only lead to rapid overheating. Second, as metal wires get smaller, the gust of electrons moving through them becomes strong enough to bump the metal atoms around, and before long the wires fail like blown fuses.

In theory, nanotubes could solve both these problems. Scientists have predicted that carbon nanotubes would conduct heat nearly as well as diamond or sapphire, and preliminary experiments seem to confirm their prediction. So nanotubes could efficiently cool very dense arrays of devices. And because the bonds among carbon atoms are so much stronger than those in any metal, nanotubes can transport terrific amounts of electric current—the latest measurements show that a bundle of nanotubes one square centimeter in cross section could conduct about one billion amps. Such high currents would vaporize copper or gold.

Where Nanotubes Shine

Carbon nanotubes have a second interesting electronic behavior that engineers are now putting to use. In 1995 a research group at Rice University showed that when stood on end and electrified, carbon nanotubes will act just as lightning rods do, concentrating the electrical field at their tips. But whereas a lightning rod conducts an arc to the ground, a nanotube emits electrons from its tip at a prodigious rate. Because they are so sharp, the nanotubes emit electrons at lower voltages than electrodes made from most other materials, and their strong carbon bonds allow nanotubes to operate for longer periods without damage.

Field emission, as this behavior is called, has long been seen as a potential multibillion-dollar technology for replacing bulky, inefficient televisions and computer monitors with equally bright but thinner and more power-efficient flat-panel displays. But the idea has always stumbled over the delicacy of existing field emitters. The hope is that nanotubes may at last remove this impediment and clear the way for an alternative to cathode-ray tubes and liquid-crystal panels.

It is surprisingly easy to make a high-current field emitter from nanotubes: just mix them into a composite paste with plastics, smear them onto an electrode, and apply voltage. Invariably some of the nanotubes in the layer will point toward the opposite electrode and will emit electrons. Groups at the Georgia Institute of Technology, Stanford and elsewhere have already found ways to grow clusters of upright nanotubes in neat little grids. At optimum density, such clusters can emit more than one amp per square centimeter, which is more than sufficient to light up the phosphors on a screen and is even powerful enough to drive microwave relays and high-frequency switches in cellular base stations.

Indeed, two companies have announced that they are developing products that use carbon nanotubes as field emitters. Ise Electronics in Ise, Japan, has used nanotube composites to make prototype vacuum-tube lamps in six colors that are twice as bright as conventional lightbulbs, longer-lived and at least 10 times more energy-efficient. The first prototype has run for well over 10,000 hours and has yet to fail. Engineers at Samsung in Seoul spread nanotubes in a thin film over control electronics and then put phosphor-coated glass on top to make a prototype flat-panel display. When they demonstrated the display last year, they were optimistic that the company could have the device—which will be as bright as a cathode-ray tube but will consume one tenth as much power—ready for production by 2001.

The third realm in which carbon nanotubes show special electronic properties is that of the very small, where size-dependent effects become important. At small enough scales, our simple concepts of wires with resistance dramatically fail and must be replaced with quantum-mechanical models. This is a realm that silicon technology is unlikely to reach, one