tiny, straw-shaped molecules a mere nanometer or so across—have been shown to conduct either like metals or semiconductors depending on their precise geometry, and they have already been incorporated into a range of electrical components such as transistors and diodes.

Reality gap

For most nanobased applications, the key to progress is straightforward: Find ways to make very fine particles or layers of material of a precise size, which, when incorporated directly into a final plastic or solar cell, all share the same electronic, optical, and mechanical properties. These simple products are already finding their way into the marketplace, and their relative ease of production might always ensure them the biggest share of the business.

Most of the buzz about nanotechnology, however, involves more sophisticated applications of nanomaterials, such as electronic devices and tiny chemical sensors. The holdup, so far, is that in most cases there's no obvious way to transform single demonstration devices into a working technology. "Nanotechnology is an area that is profoundly reductionist," says Harvard University chemist George Whitesides. "We can pick matter apart at its basic level of the atom and reassemble it." But researchers, he warns, mustn't take that ability too seriously. "We want to be sure we don't fall completely over that cliff."

Whitesides's point is that although it is possible to manipulate individual atoms, it's much harder to do it on a grand scale. In 1998, for example, researchers led by Cees Dekker at the Delft University of Technology in the Netherlands reported making the first transistor using a carbon nanotube as a key component of the device. Work since has shown that the electronic performance of such transistors can approach or even surpass that of conventional silicon transistors. "But there is a problem here," says Tom Theis, who heads physical sciences research at IBM's Thomas J. Watson Research Laboratory in Yorktown Heights, New York. When it comes to making computer chips containing millions of such devices, "it's completely unmanufacturable."

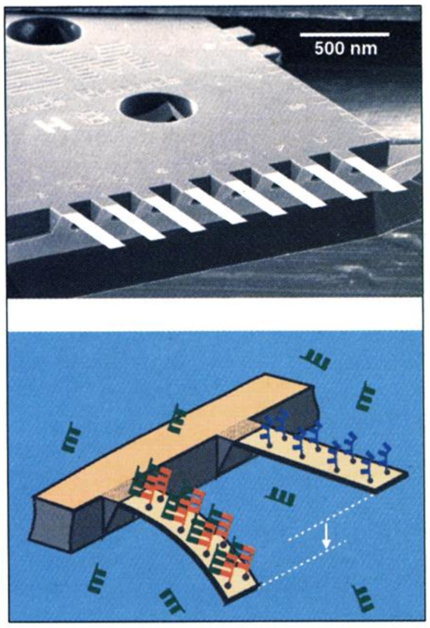
The problem of manufacturability remains nanotechnology's Achilles' heel, particularly for the much-hyped possibility of creating nanosized machines. "The technology is still almost

Cantilever Tales

Building even the simplest nanomachines is a daunting challenge, but working models serve as springboards to grander designs. A classic example is the cantilever, an indispensable cog in the nanoworld that ushered in the scanning probe microscopy revolution. Today cantilevers, which resemble tiny diving boards, are the operating principle behind a host of experimental devices that could debut in the next decade.

Nanosized cantilevers earned their claim to fame in the mid-1980s with the invention of atomic force microscopes (AFMs). To chart the surfaces of molecules, AFMs run the tip of a cantilever across an object under investigation; intermolecular forces between probe and object tug the cantilever tip up and down over the surface, like the stylus of a record player. A reflected laser beam records this motion, and the signal can be converted into an image of the surface.

Cantilevers are proving to be more versatile than anyone imagined. Perhaps it's no surprise that a pioneering center for manipulating these tiny tools is the IBM Zurich Research Laboratory in Switzerland, the birthplace of scanning probe microscopy. "The whole field was started right there," says Naomi Halas, a specialist in applying nanotechnology to chemistry at Rice University in Houston. One master cantilever builder at IBM Zurich is James Gimzewski, leader of the Nanoscale Science group. He and his team set the pace for the rest of the field, Halas says: "When they publish something, it is usually the first and best for a long time."



Flexitime. DNA-coated cantilevers bend as strands bind with their complements.

CREDIT: IBM ZURICH RESEARCH LABORATORY

The key to the next generation of cantilever devices is being able to make the miniature planks bend on demand. One approach is to coat the top surface of an AFM cantilever, a blade of silicon about 500 nanometers long and 100 nanometers wide, with short DNA chains called oligonucleotides. The researchers next expose these coated cantilevers, which are in solution, to oligonucleotides with a complementary sequence of base pairs. When the matched pairs bind, they exert an intermolecular force that expands the coating, bending the cantilever downward much as the bimetallic strip in a thermostat curls in response to temperature changes.

A scanning laser can measure the extent to which the oligonucleotide pairs bend the cantilever; the more base pairs that match, the more the cantilever bends. Thus coated, cantilevers might serve as sensitive probes for specific DNA sequences. "We were able to detect a single [base-pair] mismatch," says Gimzewski, whose team described its advance in *Science* (14 April, p. 316). This proof of principle has attracted attention from biotech companies, which view cantilever setups as potential rivals to DNA arrays for searching for genetic sequences of interest, including disease genes. "We are now trying to make [coated cantilevers] into a general-purpose diagnostic technique," Gimzewski says. "This is a new area. There aren't many sensitive tools around."

But cantilever-based devices need not be constrained to having the action—or molecules—come to them. They might be used as smart gates that release drugs or other chemicals in response to precise molecular signals. For instance, an anticancer pill equipped with cantilever gates might unleash a powerful drug at the site of a tumor only when a tumor-specific protein gloms onto a specially tailored molecular adhesive coating the cantilevers. Or a chemical for cleaning up a hazardous spill might be stored in pellets and released only when the target pollutant tugs at a cantilever gate, "rather than putting chemicals all over the place," Gimzewski says.

Closer to reaching the market, however, are cantilevers for computer data storage. In a project called "Millipede" spanning several labs at IBM Zurich, scientists are testing an array of about 1000 cantilevers as a new way of building nanoscale memory devices. Piezoelectric signals would tell the cantilevers when to jab their hot tips at a polymer film. The impressions in the film would record the data in a much denser format than current media do. "That has the potential to displace magnetic technologies," Gimzewski says. That bold prediction, no doubt, will be heeded in the nano community: Gimzewski's group has a track record for coming through. "I always aim very high and fail a lot of the time," he says, "but the few things in which I succeed make an impact and are extremely enjoyable."

—ALEXANDER HELLEMANS

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