A Small Revolution Gets Under Way

The 1990s will reveal a different side of miniaturization, one in which shrinking the size of materials and devices means not just a quantitative change but qualitative ones as well

SCIENCE • IN THE • '90s

This issue is Science's *first of the 1990s. What better place to begin a ten-part series on what the decade holds for science? Kicking off the series, which will appear in alternate issues of* Science, *is the following pair of articles. Their subject is scientists' emerging capacity to manipulate matter on the level of individual atoms, a capacity that has profound implications for fields as diverse as materials science and the design of new drugs.*

The new series—"Science in the '90s"—is not intended to be encyclopedic. Instead, it will look selectively at developments that promise revolutionary changes in how science is done. Not all these developments are research results. Some are advances in technique. Still others are major changes in the social or political climate of science. What they share, however, is the scope to cut across traditional scientific disciplines and the power to transform science as we know it.

MAKING THINGS SMALL IS NO BIG DEAL anymore. Scientists cram millions of transistors onto a computer chip the size of a fingernail. It's an old story. They store an encyclopedia on a magnetic disk the size of a dinner plate. Yawn. There's just not much more to say about the pursuit of the small.

That's the conventional view, but it's wrong. It may seem as if the ability to manipulate matter on a smaller and smaller scale is nothing more than a series of incremental advances, but recently that technology has reached the point where it opens the door to fundamentally new science. Researchers in a number of fields are finding that when something shrinks enough—whether it is an electronic circuit, a motor, a film of lubricant, or an individual crystal of metal or ceramic—that thing stops acting like a miniature version of its larger self and starts behaving in new and strange ways.

In the 1990s one of the major themes of physics, chemistry, and materials science is likely to be the study of how matter behaves at a scale of nanometers—billionths of a meter. The ability to design and manufacture devices that are only tens or hundreds of atoms across promises rich rewards in electronics, catalysis, and materials. The scientific rewards should be just as great, as researchers approach an ultimate level of control—assembling matter one atom at a time.

There is more than one way to manipulate matter on the nanometer scale. Two fundamental approaches are from the "top down" and from the "bottom up." In the top-down method, researchers start with relatively large pieces of material and carve them into smaller bits.

Take, for instance, the quantum-well laser, which is used extensively in fiber-optic communications. The active element, called a quantum well, is a layer of semiconductor material doped so that the free electrons in the device fall into the well and cannot get out. The quantum well is only a few nanometers thick—so thin that the electrons in it are effectively moving in only two dimensions, giving the device novel properties. For example, the frequency of the laser light can be modified merely by changing the well's thickness—a feature with no parallel in normal lasers.

Like other semiconductor devices, the quantum-well laser is produced by molecular-beam epitaxy, a process that can deposit layers of material as thin as a single atom onto almost any surface. Once the layers are in place, x-ray or electron-beam lithography carves out features. State-of-the-art techniques can etch lines as small as 20 nanometers—only 100 atoms—across. Various technical problems, however, make the practical limits of fabrication somewhat larger.

As these limits are overcome and devices become smaller, new physical phenomena will probably be discovered—as was the case when researchers first studied quantum wells. Jim Harbison, a solid-state physicist and materials scientist at Bell Communications Research, says scientists are particularly eager to study the behavior of quantum lines and quantum dots—the analogues to the quantum well, but with the electrons confined to one or zero dimensions.

Quantum effects of a different sort appear when shrinking other devices, such as computer memory. John Foster, a manager of molecular studies for manufacturing at IBM's Almaden Research Center in San Jose, California, notes that the magnetic head on a standard computer hard disk travels 60 to 100 miles per hour at a distance of only 200 nanometers above the disk's surface. "It's like flying a 747 at full speed 1 inch off the ground," Foster says. And IBM has now developed a prototype storage device whose head stays less than 50 nanometers off the disk. At these scales, the physical laws that govern phenomena such as the flight of a 747 no longer apply, and researchers must start over to understand how to keep the magnetic head flying and landing smoothly.

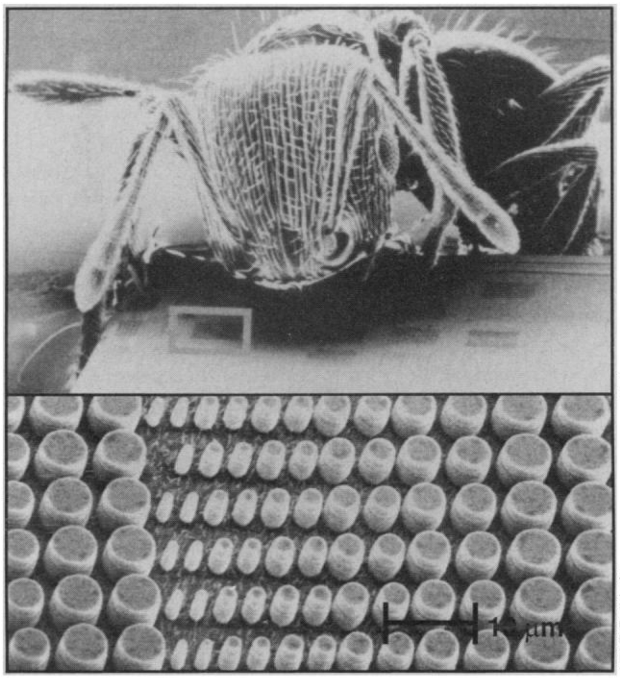
In particular, since the head drops onto the hard disk whenever it stops, the disk needs lubrication for times when the head "lands" or "takes off." The layer of lubricant is only about 1 nanometer thick, and because of its scale it behaves quite differently from normal lubricants. Last year, Jacob Israelachvili of the University of California, Santa Barbara, showed that at such small scales frictional forces are quantized: A layer of lubricant aligns itself into a whole number of molecular layers. (In the case of the hard disk, there are usually two monolayers of lubricant molecules.) The friction too is quantized and depends only on how many monolayers there are.

Instead of the top-down method, researchers such as Richard Siegel take the opposite tack, piecing together bits of matter to form materials with properties quite different from any seen before. Siegel is a materials scientist at Argonne National Laboratory. His version of the "bottomup" approach involves making metals and ceramics out of powders with grains on the order of 10 nanometers across. In case after case, Siegel finds that the products behave much differently from materials with the same chemical composition but larger grains. Palladium formed from 5-nanometer grains, for instance, is five times as hard as normal palladium, whose grain sizes are in the micron (1000-nanometer) range. And the ceramic TiO_2 is four to five times more ductile with 10-nanometer grains than with normal-sized ones.

Siegel's work relies on a technique invented in 1981 by Herbert Gleiter at the University of the Saarland in Saarbrücken, West Germany. Gleiter made clusters containing thousands to tens of thousands of metal atoms by evaporating the atoms from a metal source, then putting them in a chamber filled with an inert gas, where they condensed into clusters. The clusters can be collected and sintered (heated until the grains stick together) to form bulk samples.

Because the grains are so small, these "cluster-assembled materials" can be sintered at temperatures hundreds of degrees lower than those used in conventional processing of metals or ceramic. The lower temperature makes processing more convenient. In addition, because higher temperatures cause grains to grow together, it permits much greater control over the size of the grains in the final product. And grain size, Siegel says, seems to be the key to many of the materials' properties.

The bottom-up route can also be taken by chemical rather than physical means, as Rustum Roy of Pennsylvania State University has shown. In his "sol-gel" method, Roy suspends ceramic molecules, such as Al_2O_3, in a liquid solution and then causes them to precipitate out. Heating the precipitate "burns out" everything but the ceramic, leaving homogeneous material with nanometer-sized grains. The technique is not new—industry already applies it to make materials such as films and fibers—but recently Roy came up with the idea of using it to mix two different compounds to create "nanocomposites." These materials have grain sizes on the order of 10 nanometers—much smaller than the grains of normal composites—and have a whole range of novel hybrid properties.



Ant meets laser. *An array of 1 million quantum-well lasers of various sizes fits into an area the size of a fingernail.*

Nanocomposites are a promising new breed, and a number of laboratories are working on them. In some of those labs the intrinsic properties of materials are being exploited to yield "self-forming nanocomposites" that actually order themselves on a very small scale. Robert Newnham at Penn State described a material made of niobium, magnesium, and lead that spontaneously creates domains as small as a few nanometers across. The compound has small crystalline regions where the niobium and magnesium are in a one-to-one ratio surrounded by areas that are predominantly niobium.

Some researchers have taken the idea of small assemblies of atoms to its limit and are forming clusters with only a few atoms. These microclusters have properties that are different not only from larger collections of atoms, but also from each other, depending on the number of atoms in the cluster. For instance, researchers at AT&T Bell Labs have measured the reaction rates of silicon microclusters with ethylene, C_2H_4, and found that 12-atom clusters, Si_{12}, react 1000 times faster than clusters with only one more atom, Si_{13}.

The reason, notes Bell Labs' Walter Brown, is that the shape of the cluster changes drastically with the addition or subtraction of one atom—and its shape determines many of its chemical properties. Furthermore, a Si_{12} or a Si_{13} cluster has properties completely different from bulk silicon or even nanometer-sized clusters with thousands of silicon atoms. The atoms in bulk silicon and in the interior of a 10-nanometer grain align themselves in a specific crystalline order. A cluster with a dozen atoms, however, doesn't have an interior, and it bears little structural resemblance to a silicon crystal.

Just how unusual microclusters can be was demonstrated several years ago in the form of "soccerene," a substance discovered by Richard Smalley of Rice University. In bulk, carbon atoms tend to align themselves in the layered structure of graphite or even in the three-dimensional array of diamond, but Smalley found that small numbers of carbon atoms have their own preferred structures. The most striking is soccerene: a collection of 60 carbon atoms arranged much like the geometric shapes sewn together to yield a soccer ball. Soccerene is a very stable molecule whose atoms have little tendency to interact with other atoms. As a result, some researchers think soccerene would be a good protective coating for such devices as electronic circuits.

Although microclusters are fascinating objects, the ultimate in manipulating matter will be to put molecules together atom by atom. Some scientists are already working on that. Researchers working with the scanning tunneling microscope (STM) reported last year that they had succeeded in cutting a molecule in two by bringing the tip of the STM down on top of it and running a large enough current through it to break the molecular bonds. Foster at IBM reports that researchers there have now "whittled down" a molecule from 12 angstroms across to only 4 angstroms. "We can't control as well as we'd like where it will break," he says, "but we think in the future we'll be able to."

To put molecules together with the STM instead of breaking them apart, researchers will have to learn how to move molecules on a surface and how to join them once they're close together, Foster says. To move them, researchers are trying a technique called "molecular herding," in which the tip of the STM circles the molecules much as a sheep dog circles recalcitrant sheep. Investigators already have no trouble getting the molecules to move, Foster says, but making them go where they are supposed to is something else again.

Within the decade, Foster or some other scientist is likely to learn how to piece together atoms and molecules one at a time using the STM. Meanwhile, other researchers will be exerting increasingly precise control over nanometer-scale matter with such tools as lithography or cluster techniques. The real news, though, won't be the techniques themselves. It will be the fact that these techniques are opening an entire new physical realm for investigation and control. In the 1990s making things small will be very big. ■ ROBERT POOL