Microscopic Motor Is a First Step

Using the same technology that allows the fabrication of thousands of transistors on one tiny computer chip, researchers are building ultra-miniature machines

A TINY MOTOR no wider than the thickness of a human hair has been built by researchers at the University of California at Berkeley. Static electricity turns the rotor hundreds of revolutions per minute. Although it is a very simple device, it may herald the development over the next few decades of micromachines with important uses in such diverse areas as medicine, communications, and manufacturing.

The micromotor, made of silicon, is one of the first successes in an effort to build miniature machines not much larger than the individual elements on computer chips. These micromachines will be tens or hundreds of micrometers in size and, according to some predictions, could change technology as dramatically as did the miniaturization of electronics by the invention of the transistor and the integrated circuit.

First, however, researchers must answer a number of basic science and engineering questions about how materials behave at such tiny dimensions.

The quest to build machines nearly invisible to the naked eye has two motivations. One is purely practical: Micromachines could have valuable applications in a number of areas. A recent report published by the National Science Foundation suggested such possible uses as ingestible "smart pills," which would sense chemical levels in the bloodstream and dispense doses accordingly; tiny auger-like cutters that could be used to cut through blockages in blood vessels; and delicate devices that could sort individual human cells in order to make various diagnostic tests, such as counting white blood cells.

Already, tiny silicon diaphragms built on electronic chips are being used to gauge air intake pressure in automobile engines, and some enthusiasts have predicted such miraculous mechanisms as cell-repair machines that travel through the body killing viruses, dissolving blood clots, and destroying cancer cells.

The second motivation for building micromachines is to understand how devices function on such a tiny scale. The physical forces that affect machines—friction or stress forces, for example—may behave much differently on a scale of micrometers than on a scale of centimeters, and the only way to understand forces at such scales is to build microdevices and test them. Microfabrication offers scientists a whole new arena in which to form and test theories.

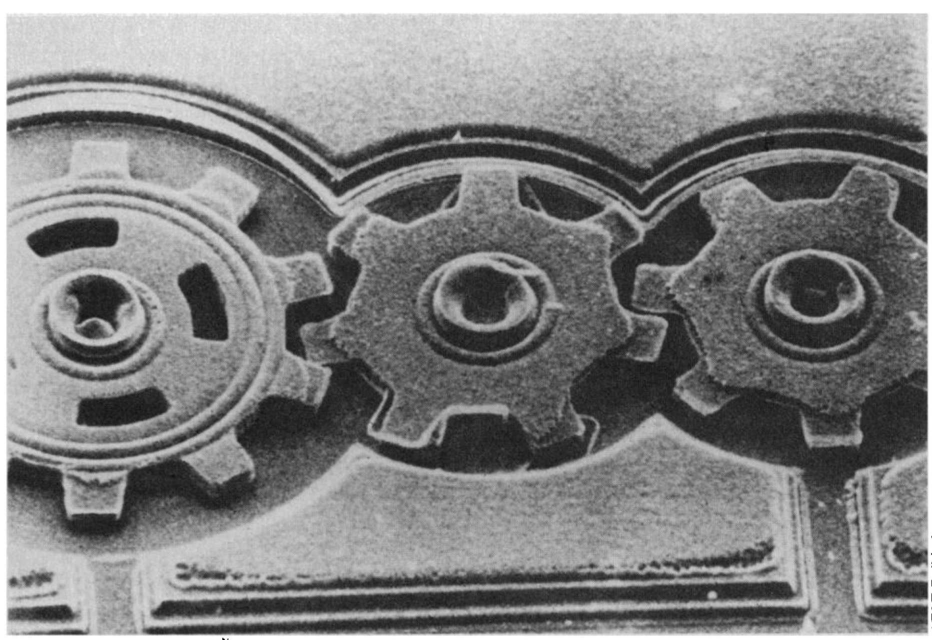
So far, the micromachines that have been made are very simple devices—levers, gears, sliding blocks. The first micromotor that turns continuously under electric power was built 2 months ago by Richard Muller, an electrical engineering professor and co-director of the Berkeley Sensor & Actuator Center. Researchers in the field say these are the first small steps toward what will eventually be very complicated and very versatile machines, and often draw an analogy with electronics, where miniaturization opened the door to previously undreamt of applications.

In fact, it is the technology developed over the past two decades to do semiconductor manufacturing that has allowed researchers to begin experimenting with microfabrication. Industry and government spent many billions of dollars to develop techniques of shaping silicon and other materials into computer chips, and that knowledge can be applied rather directly to make microscopic mechanical devices.

Semiconductors are made by laying down thin layers of various materials, mostly silicon and silicon-based, in various shapes, usually lines and rectangles. The same techniques and even the same manufacturing machines are used for microfabrication.

This has its advantages and its disadvantages. One of the advantages is that as long as the same manufacturing techniques are used for both microelectronics and microfabrication, the two technologies can be integrated easily. Muller said that because communication with and control of micromachines is likely to be through integrated circuits, it is important to keep the two technologies compatible. For that reason, he said, he tries to use microfabrication techniques that are as close as possible to semiconductor manufacturing techniques.

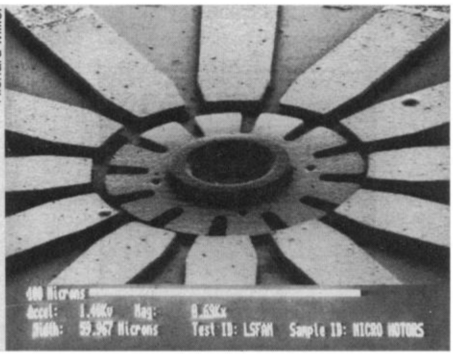
A disadvantage of using the semiconductor technology is that it is specialized for making the flat, two-dimensional structures of integrated circuits. "Everything is optimized for the thin film, not the thick film, regime," said Greg Galvin, deputy director of the National Nanofabrication Facility at Cornell University. (Nanofabrication is the next smaller step down from microfabrication, where devices are made on the scale of nanometers, or thousands of a micrometer.) It is no accident that most or all the microdevices made with semiconductor technology—gears, rotors, levers, and so on—are very flat. It will not be easy to modify this technology to make objects with a great deal of height.

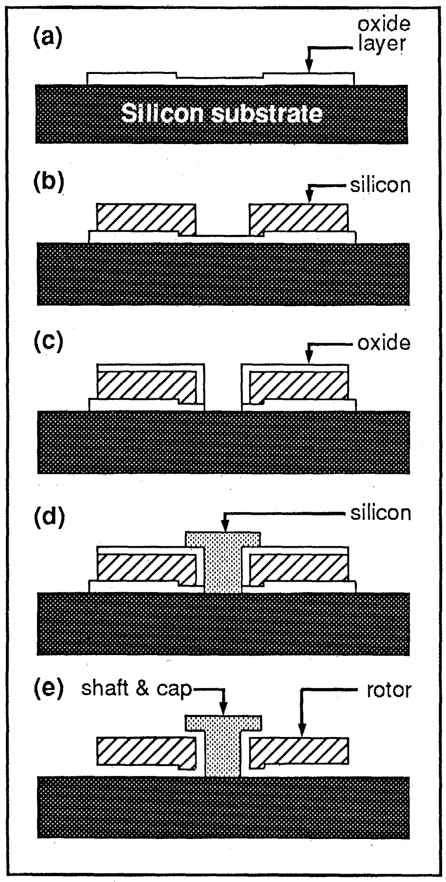


AT&T Bell Labs

A miniature turbine. *Air enters through the channel at bottom and turns the gears.*

Richard Miller





Building a micromachine. *A static electricity motor such as the one pictured above can be fabricated in a series of steps, right. First, (a), a disc-shaped oxide layer is deposited (it looks rectangular in cross section) on a silicon substrate, then a ring of silicon (b) and another oxide layer (c). A cylinder of silicon is deposited into the hole in the oxide layer (d). When acid is applied to the entire piece, it eats away the oxide and leaves the silicon relatively intact, so that only a gear and a hub mounted on the substrate remain. (e).*

The effort to develop micromachines follows three lines of inquiry. First, researchers must understand the mechanics of such small devices—how friction, wear, abrasion, lubrication, stress, deformation, fatigue, and other factors behave at this level. They also must learn about the material properties of the various substances that could be used in micromachines and determine which are appropriate for different jobs, as well as look for the best ways to design and build the devices.

In practice, since it is a new field, researchers tend to pursue two or all three of these different lines concurrently. They design and make the devices, and then test them to see how the tiny machines behave under various conditions.

The first step, then, is to try to build the micromachines. Semiconductor manufacturing consists of laying down a series of patterned layers of different materials atop a silicon substrate, and sometimes etching away parts of the layers with acids. A micromachine can be made in much the same way, with the major difference being that one will probably want moving parts on the machine. For a part to move, it must be freed from the substrate, and this is done by making the part on top of a "sacrificial layer." This layer is made of a material much less resistant to acid than the part itself, so that when the entire piece is washed with acid, the sacrificial layer dissolves and leaves the part above it unattached.

By cleverly designing the fabrication pattern, researchers can form freely moving gears and other parts that are attached to the substrate with hubs. (See illustration above.) As a result, the machines are already completely assembled once they are formed. This is fortunate because assembling parts that are tens of micrometers in size would be somewhat challenging.

Once the machines are built, researchers can test their mechanical properties. "You want to build a little system and watch it fall apart," said Kaigham Gabriel at AT&T Bell Labs. Since semiconductor manufacturing technology is designed to make hundreds or thousands of identical components at the same time, researchers will be able to perform the same tests over and over again, he noted.

By moving the rotors and gears, researchers can test how the materials—mostly silicon at this time, since that is the standard semiconductor material—react to stress, wear, frictional forces, static electricity, and other effects. At Bell Labs, scientists have used jets of air to rotate a rotor at more than 15,000 revolutions per minute. "The key thing here is that silicon has come off the substrate for the first time," he said, and this allows researchers to test its mechanical properties.

The static electricity motor at Berkeley will provide an opportunity to measure mechanical properties under varying conditions, Muller said, since its rotational speed can be governed. "We now have a controllable force," he said, and that will allow such measurements as static friction and running friction at various speeds.

Micromachines can be expected to have different mechanical, electrical and thermal properties than identically shaped machines of macroscopic dimension simply because they are within a few orders of magnitude of atomic size.

For instance, the micromachines now being made are about the same length as the mean-free path of air molecules, or the average distance a molecule travels in air before striking another molecule. This implies that the viscous drag of these machines in air (or liquid) is likely to be much different than normal-sized machines. For a similar reason, static electric charges behave much differently on micrometer-sized devices than on larger ones.

As researchers examine the mechanical properties of microdevices, they will also be testing different materials. Silicon has turned out to be surprisingly strong mechanically and so it has been a good material to serve as the basis for micromachines, but other materials will also be needed. Silicon nitride, for example, is a very hard material that might serve in bearings. And Muller said it should be possible to find a lubricant, but no one has tried anything yet.

Microfabrication researchers must also learn to modify semiconductor manufacturing techniques so as to avoid their disadvantages for making mechanical devices, yet keep compatibility between the two technologies. The furnaces used in laying down layers of silicon, for example, can generally apply about 5 micrometers before they must be cleaned. This is enough for maybe 50 runs of computer chips, but only enough to make a single mechanical gear. And the thicker layers used in microfabrication will demand the development of new etching techniques that can avoid the rough surfaces that now generally result when etching thick films.

Researchers say it will be vital to maintain compatibility between semiconductor manufacturing and microfabrication. "When you begin incorporating electronics [into micromachines], that's when the real advances will come in," Gabriel said. The first combinations of the two technologies could be something as simple as putting tiny fans on integrated circuits to keep the electronics cool. After that, who knows? After all, when microelectronics were first being developed, no one predicted they would eventually be used to control the movements of children's dolls, to build radar detectors, or to create an entire new industry: desktop publishing. The consumer market is wide open.

■ ROBERT POOL