Making Micromachines

Feature

by Eric J. Lerner

Producing micromechanical devices such as pressure sensors by techniques similar to those used for making microcircuits has become routine. Mechanical and optical devices less than a millimeter across—often far less—have entered the marketplace. Until recently, however, production techniques limited both the size and the variety of micromachines that could be built. But now, new processes are making possible the production and assembly of more complex three-dimensional devices and much smaller, nanoscale devices as well, such as the Swedish walking microrobot illustrated in this article. Laser-based micromachining is beginning to supplement the chemical etching techniques long in use.

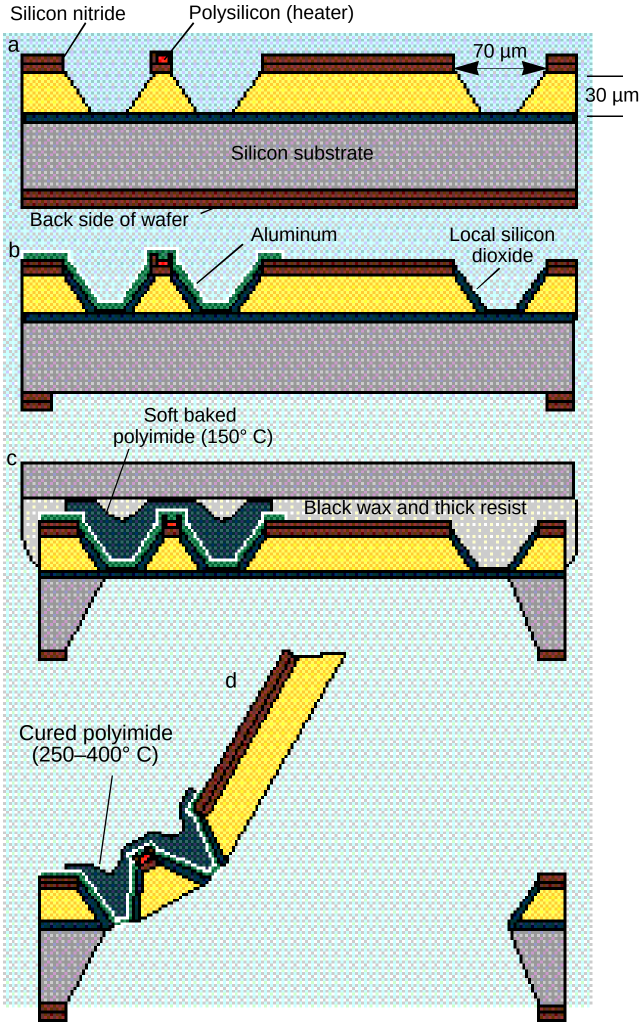
Production options expand for ever more sophisticated devices

The most widespread technique for making micromechanical and micro-optical devices relies on the same photolithographic approach long used to craft microcircuits. That is, a pattern is first embodied in a lithographic mask. Then the workpiece is overlaid with a resist, a photosensitive material that is exposed to light that passes through the mask. Where the resist is exposed and chemically transformed, it is then chemically etched away, as is the underlying layer of the chip, thus transferring the pattern in the mask onto the chip.

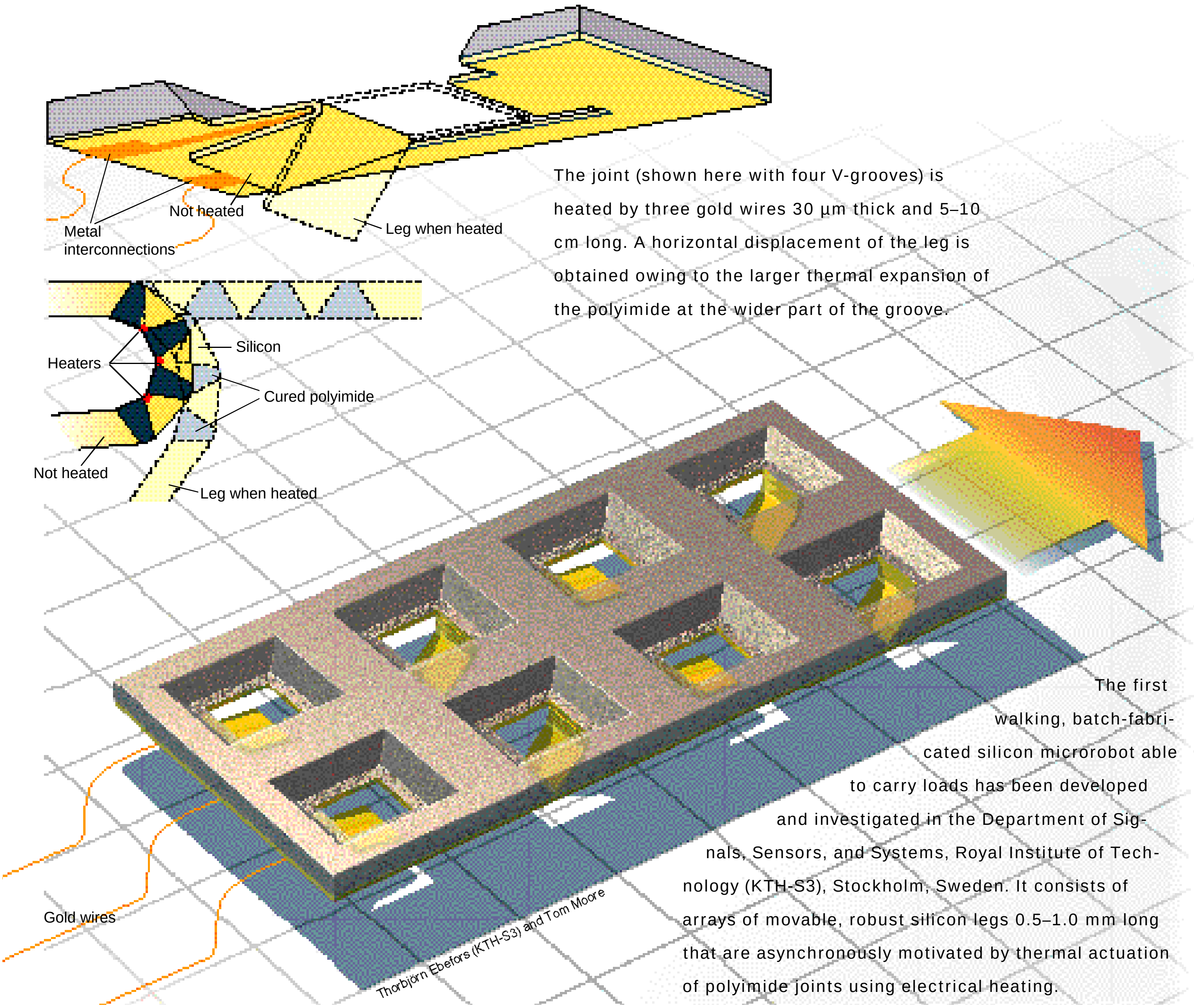
What differentiates the process used in producing micromachines from that used in producing microcircuits is the necessity to liberate parts of the machine from the underlying layers so they can move. For example, in an accelerometer used in such devices as seat-belt interlocks (see *The Industrial Physicist*, 9/98, pp. 46–47), a tiny cantilever beam must be able to move, so a region of material has to be cut from underneath the cantilever to free it. To produce such undercut regions, which are essential to most micromachining, a layer between the substrate and the overlying cantilever, known as a sacrificial layer, is etched away from the side.

Existing techniques using sacrificial metal layers have several drawbacks. First, applying the layers tends to be costly. Because thermal evaporation of the layer onto the substrate does not yield good-quality films, plasma sputtering is generally used. However, this involves relatively expensive equipment and slow rates of coating. In addition, dissolving the sacrificial layers is difficult because strong acids are needed to attack the material from the edge in a reasonable length of time, yet the acids must not dissolve the substrate or the overlying layers that need to be freed to move.

To overcome some of these difficulties, recent research has turned to the photoresist materials themselves as sacrificial layers. This process, developed at the Rutherford Appleton Laboratory in Oxon, England, has several steps. First a relatively thin layer of photoresist (several micrometers thick) is laid down and patterned photolithographically. The remaining photoresist, after etching, is then flooded with ultraviolet radiation to make its later removal easier. Second, a thin electroplate is laid down on the photoresist to protect it in the next step, in which a thick



Key fabrication steps for a microrobot leg include: (a) forming the integrated heater and etching V-grooves; (b) local silicon dioxide growth and patterning the sputtered aluminum conductors; (c) placing the polyimide in the V-grooves, etching the silicon back side, and saw dicing the chips; and (d) etching to release the leg and a polyimide cure to erect the leg.



The joint (shown here with four V-grooves) is heated by three gold wires 30 µm thick and 5–10 cm long. A horizontal displacement of the leg is obtained owing to the larger thermal expansion of the polyimide at the wider part of the groove.

The first walking, batch-fabricated silicon microrobot able to carry loads has been developed and investigated in the Department of Signals, Sensors, and Systems, Royal Institute of Technology (KTH-S3), Stockholm, Sweden. It consists of arrays of movable, robust silicon legs 0.5–1.0 mm long that are asynchronously motivated by thermal actuation of polyimide joints using electrical heating.

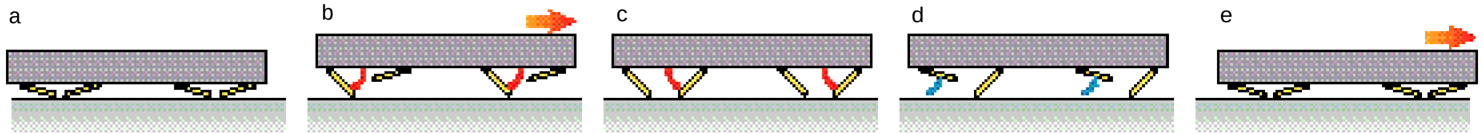
Thorbjörn Ebefors (KTH-S3) and Tom Moore

layer of resist is laid down and again patterned with a mask, with portions then etched away.

These initial steps create a pattern of resist that occupies the space that will be emptied out to allow the free movement of the micromechanical part. The metal micromachine parts are then electroplated on top of the photoresists. Finally, the resist is etched way, freeing the machine parts to turn or vibrate. The research team at Rutherford has successfully demonstrated this process in building electric motors and other structures that measure less than 0.5 mm across.

Instead of powerful acids, this process employs the same chemicals used in conventional lithography to dissolve the photoresists and expose underlying layers. The chemicals have no effect on the metal parts themselves. In addition, depositing the photoresist is an inexpensive and fast process, unlike plasma sputtering.

Generating micromechanical parts and freeing them to move away from the substrate is not the whole task for many micromechanical and micro-optical devices. Especially with optics, parts such as mirrors and lenses have to be swung out of the plane of the substrate and



The robot “walks” by mimicking an insect. (a) Rest position; (b) legs 1 and 3 move down, inching the robot forward; (c) legs 2 and 4 move down; (d) legs 1 and 3 move up; (e) legs 2 and 4 move up, inching the robot forward.

Thorbjörn Ebefors tests the weight-carrying capacity of his microrobot. The robot can carry a load exceeding 40 times its own weight.

Steering to the left and right is achieved by driving forward on one side and back on the other, making longer strokes on one side, or increasing the frequency of steps on one side.

remain there to be functional (see *The Industrial Physicist*, 9/98, pp. 39, 41–42). Many methods are used to accomplish this, all having drawbacks and strengths. They differ primarily in how the hinges that lift the part are activated and in how the parts are fixed into place.

Many current actuating approaches rely on some form of chemical processing or mechanical agitation of polysilicon or aluminum hinges, which temporarily lift the hinges up, and a system of interlocking braces that prevent them from falling back. Often, turbulent water is used to simply jostle the interlocking flaps into place. Unfortunately, these hinges are often fragile and the interlocking braces do not work for all types of devices. An alternative is to use integrated heaters to bend shape-memory alloys, but this method makes it hard to isolate different links because of thermal conduction. Also, large bending radii are required, which limit how small one can make devices. Similar bending radius limits apply to bimetallic strips, which can be activated either by thermal changes or electrical gradients.

As a result, research is continuing into new, more versatile alternatives that can generate smaller radii of curvature. One idea, developed at Sweden's Royal Institute of Technology (Stockholm), uses polyimide V-grooves to form hinges. The polyimide shrinks as it is thermally cured, resulting in the contraction and bending of the V-groove. For large bending angles, several V-grooves can be used in series. Bending radii of 50 μm have been achieved, and smaller radii can be reached with thinner grooves and silicon beams.

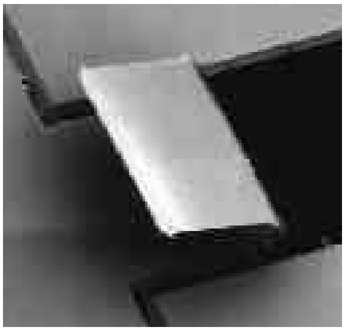
Another new idea, pioneered at the University of Illinois' Microelectronics Laboratory, relies on magnetic forces to bend the flaps out of the plane. Here, a small bit of Permalloy, a magnetic material, is attached near the end of the flap. When a magnetic field is applied perpendicular to the substrate plane, the resulting interaction with the Permalloy magnet lifts the flap up. The position of the flap results from an equilibrium of the magnetic force with the stiffness of a spring mechanism on the hinge. Again, interlacing flaps can be used to maintain the structure after the magnetic field has been removed, or the field can be varied to control the tilt of parts, as in scanning mirrors.

Lasers

While lithographic processes are almost exclusively used to make the micromachines now on the market, research on laser micromachining is at an advanced stage. Compared with chemical techniques, laser micromachining has definite advantages. First, lasers can be used to machine metals, whereas lithographic techniques are used almost exclusively for silicon wafers, with metals added by electroplating. Second, lasers are capable of fabricating much smaller dimensions than current silicon-based techniques. Lithographic techniques generally produce devices with dimensions of tens of micrometers, compared with the few micrometers possible with conventional laser micromachining and the nanometer scales that may be achievable with more exotic techniques

Laser micromachining systems consist of a laser source, optics for conditioning and focusing the beam, and some method of precisely controlling and pointing the beam. Laser sources are usually either excimer lasers or Ti:sapphire femtosecond pulsed lasers, although Nd:Yag lasers are also used. The advantage of excimer lasers is that their UV radiation is absorbed strongly by practically all materials. This feature allows the laser energy to be absorbed in a very small region, although it also makes optics for the systems tricky. Femtosecond pulses also can create very fine ablation patterns, as the energy is absorbed by electrons before there is time for adjacent atoms to be heated. The limited region of heating reduces damage to the neighboring areas. In some cases, the two technologies are combined, with excimer radiation delivered in less than a picosecond. Ti:sapphire systems also can be compact and all-solid state. However, for many micromachining applications, the workhorse Nd:Yag lasers with longer nanosecond pulses are quite adequate.

Very small pulses can be used, with a few hundred microjoules of energy being sufficient to ablate a 100-μm-wide focal spot. Typical micromachining lasers have average power outputs of only 50 mW to 2 W and pulse energies from several tens of microjoules to several millijoules. Two basic approaches are use to control the laser



Scanning electron microscope close-up of a micro-robot leg (left) and V-groove joint actuator (right).

beam irradiation of the workplace—either uniform illumination of a mask or direct writing with a point source beam. When masks are used, optics shrink the resulting image and focus it on an area typically 5 to 15 times smaller in linear dimensions than the mask. In direct writing, either the direction of the beam is controlled by a mirror or the workpiece itself is moved on a stage.

For example, in experiments performed at BNFL Springfields (Preston, England), a facility of the corporation formerly known as British Nuclear Fuels, 170-fs pulses from a Ti:sapphire laser operated at 790 nm were used to ablate channels into fused silica and Pyrex. The pulses were focused to 50 μm in diameter, and the workpiece was moved on a translation stage. Initial experiments in ablating tracks with 500 μJ/pulse, a 1-kHz pulse rate, and 1-mm/s scan rates showed severe cracking at the edges of the track. But reducing the energy to 50 μJ/pulse and increasing the scan rate to 7 mm/s created cleaner and shallower trenches. Deeper trenches were then formed by laser milling—repeatedly ablating the same trench but reducing the width milled at each pass to form a triangular trench. In this way, surface roughness was reduced to below 1 μm.

Beyond micromachining

While laser micromachining techniques are still under laboratory development, researchers are also looking to additional techniques that will further expand their ability to create extremely small devices. One approach generates microstructures by adding as well as subtracting material. Scientists at the Institute of Electronic Structures and Lasers (Athens, Greece) have shown that with femtosecond UV radiation, lasers can precisely transfer material through ablation to a workpiece. A laser was focused on a chromium film on transparent quartz wafers, and a glass target surface was placed in near proximity to the film. Then, 500-fs pulses at 248 nm were used to ablate the chromium from the film and deposit it onto the glass. In this way, 4-μm-diameter dots could be reliably placed onto the glass at a rate of 10 pulses/s.

In another area, the size of laser-generated trenches is being reduced from the micrometer to the nanometer scale by the use of near-field optics. The Folant method (focusing of laser radiation in the near field of a tip) uses field enhancement in the near field of a scanning tunneling tip, generally employed in scanning tunneling microscopes (STMs) capable of observing individual atoms. In work performed at Physikalische Technik Laserlabor (Steinfurt, Germany), a frequency-doubled Nd:Yag laser at 532 nm is focused on the gap between the tip of the STM and the work region. In the immediate vicinity of the tip, the field is greatly enhanced by a combination of Rayleigh scattering and surface plasma excitation. For metal tips, the field enhancement is about a millionfold.

With tungsten tips having a 30-nm radius of curvature, this method carves line cuts in a gold or palladium surface that are only 15 nm across. Such narrow cuts could lead to the production of devices several orders of magnitude smaller than any now produced. The actual mechanism of trench production is likely to be some combination of field enhancement and physical contact between the tip and working material, and this will require more study.

Tungsten tips can themselves be fabricated with new nanoscale techniques. Conventional tips are fabricated one at a time and have poor consistency in point size. But many applications, such as information storage, require tens of thousands or even millions of identical tips. One path to such nanofabrication first uses ordinary lithography with a positive resist to produce pillars of tungsten. (A positive resist is one in which the areas exposed to light resist etching while those not exposed are etched away.) The resulting 100-nm-wide pillars are then further etched by electron beams, producing more uniform tip sizes. This interaction of smaller tips for nanoprocessing and smaller nanomachines could lead to the next leap downward in machine size to a level not much above the atomic scale.

Many of the newer micromachining techniques will require considerable development before they are ready for mass production. However, as these more flexible technologies move out of the laboratory, the field of applications for micromachines should expand greatly.

For further reading

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