Developers are pushing processing boundaries to give new dimensions to the world of MEMS. By Leo O’Connor and Harry Hutchinson

**FEATURE FOCUS**

MICROELECTROMECHANICAL SYSTEMS” is not one of those phrases you say lightly without practice. But “MEMS,” on the other hand, is a different matter. Short, almost warm, it could be a child’s term of endearment for Mother.

The image of MEMS is right up there with Mom and mince pie, too. As an enabling technology, the tiny devices are linked to medical marvels, car safety, and computer chips—so many of the day’s sacred icons.

That’s why researchers across the country are out to devise ways to improve on the technology, to turn out microdevices cheaper and faster, and to design them in greater variety.

Projects in the works seek to develop commercial systems that will make microelectromechanical systems taller and with more varied geometry than most current fabrication techniques can yield. Some aim to extend the range of practical materials, reduce the cost of making devices, and reduce the cost of getting into the business. The purpose is to enrich the variety of MEMS to open new applications and markets.

Established manufacturing methods for most microelectromechanical systems were developed for electronics, and so the micromachines turned out that way generally look like chips. The selection of materials is usually limited, and height, measured in microns, often remains in the single digits and rarely exceeds 20. Both limitations increase in importance as developers try to make these devices do useful work.

A typical micromachining process relies on low-pressure chemical vapor deposition or thermal oxidation and chemical etchants to define a given geometry. The process may make a suspended mass, or a slender bridge that connects to a wafer at one end. This turns out to be an extremely popular shape in microsystems because it allows measurements of such properties as acceleration and vibration.

Manufacturing processes may require vacuums or special atmospheres, or may work only at very high temperatures. The investment in a cleanroom and other equipment can cost a manufacturer more than $10 million.

**NO CLEANROOM REQUIRED**

Researchers at the University of Southern California say they are addressing many of these issues in a manufacturing system that combines an “instant masking” technique and electrochemical deposition, and can build a device of an unlimited number of metal layers. Their aim is to create an automated batch fabrication process that will use a desktop machine at relatively low temperatures, below 60°C. A significant cost saving to the method is that manufacture does not require a cleanroom.

In an interview, Adam Cohen, project leader at USC, compared the instant mask to a printing plate. Manufacturing requires a mask for each different horizontal cross section of a design. The patterns can be derived from a CAD file. Last fall, during ASME’s International Mechanical Engineering Congress in Nashville, Cohen, representing himself and five co-authors, presented a paper on the system, which they call EFAB, for electrochemical fabrication.

The system can put down one layer every 40 minutes, or three dozen a day, and a mask can be large enough to contain multiple copies of a pattern and make products in batches.

The layers can be stacked by the hundreds, or thousands, theoretically with no limit. However, a practical upper
height is about a centimeter, mainly because there are faster ways to build devices larger than that, Cohen said.

Although the manufacturing process does not require a cleanroom, making the masks does. Cohen pointed out that a manufacturer can avoid that investment by having the masks made by a fulfillment house. He estimated that, when commercialized, an EFAB system for prototyping will cost somewhere between $500,000 and $1 million.

According to Cohen, EFAB can manufacture devices as intricate as multilink chains, springs, screws, and universal joints. Monolithically fabricated integrated systems are also possible, including miniaturized motors and engines, turbines, gearboxes, chain drives, clutches, propellers, pumps, solenoids, and valves. The only type of geometry it cannot make, Cohen said, is a fully enclosed hollow space because the sacrificial material needs an outlet to be removed.

Layers are generally 5 to 10 microns thick. Although he admitted it has not been tried, Cohen said a layer as thin as 2 microns might be possible. The process can create features as small as 20 microns wide, accurate within 2 microns.

The research team has identified potential uses in high-volume industries, including inkjet printheads, thermal management devices for dense electronics packaging, and tiny butane-powered generators that can power portable electronics such as laptop computers and cell phones. EFAB also comes in handy in one of the fastest growing sectors of microelectromechanical systems manufacturing—optical devices such as switches and fiber aligners that rely on the production and transmission of light. To this end, the process could fabricate optical communications switches that direct the route of a beam of modulated light to carry information from a transmitter to a receiver.

**DEEP X-RAYS**

Work at the University of Wisconsin in Madison is proceeding with a process that uses deep X-ray lithography. The technique is derived from an established micromanufacturing process known as LIGA, an acronym derived from the German terms for lithography, electroforming, and molding.

LIGA, which has been around for a while, produces relatively tall micromachines by a method that radiates X-ray-sensitive materials to create molds. Among the companies that market products made by the LIGA process is MicroParts of Dortmund, Germany. The company offers fluidic and optical microdevices, and cites several advantages to the process, including close dimensional accuracy, integration of various geometries in one plate, and the design freedom of relatively tall microstructures.

LIGA irradiates a thick resist through a mask that's mostly transparent to X-rays but also consists of selectively placed regions of a material such as gold that absorbs X-rays. When the X-rays have changed the resist's molecular weight in selected regions, chemical etchants...
dissolve the regions that have been exposed. What remains is a mold into which a material such as nickel can be electroplated. When chemicals have removed the mold and have etched away sacrificial layers, they leave a nickel tool from which a manufacturer can fabricate parts made from a variety of materials, usually by injection molding.

Led by Henry Guckel, a professor of electrical and computer engineering, developers at Wisconsin teamed with Brookhaven National Laboratory, which provides a 20,000 eV photon source to produce radiation. According to Guckel, the X-rays are of a much higher energy level than those used in the traditional LIGA process. They enable a number of innovations, not the least of which is the elimination of injection molding.

Jumping to that energy level greatly boosts the throughput of the process. The high-energy X-rays penetrate deeper into the photoresist material, to depths of a centimeter and more, and they also pass more easily through the mask. The mask for high-energy X-rays can be made of thicker material than the mask for lower-energy photons. The thicker, and therefore stronger, material can be made into bigger masks, capable of exposing batches, to achieve volume by direct fabrication rather than by injection molding.

Instead of using a 1x6-cm X-ray mask as in the standard LIGA process, the Wisconsin team uses one that is 4 inches square. With the high-energy photon source and larger mask, the team exposes a 30,000-sq.-cm. surface of material in 24 hours. That reduces cost and time.

The Wisconsin process fires X-rays deep into poly-methylmethacrylate, or PMMA. "You'll laugh when I tell you what the photoresist is," Guckel said. "It's plexiglass." The researchers are buying it in 4x8-ft. sheets and cutting it by various methods, including water jet cutting. Then it is solvent-bonded to a substrate.

After X-ray exposure and removal of affected material, the manufacturer is left with an array of plastic microstructures, which can have deep vertical canyons in them accurate to the submicron level. Complex structures, such as overhangs, are possible by layering, Guckel said. The plastic can be electroplated to create metal structures, he added.

There are two beam lines in the Brookhaven synchrotron that are devoted to developing what is termed "high-aspect-ratio micromachining," according to Erik Johnson, the Brookhaven researcher who set up the lines.

At present, one of the lines is devoted to developing a manufacturing process and has begun to turn out optical microswitches developed by Guckel and his team in concert with Honeywell.

So far, only a few switches have been made, but the aim is to develop a system that will turn out one million pieces a year, Guckel said.

MORE MATERIAL OPTIONS

Meanwhile, research that began in the Department of Industrial and Manufacturing Engineering at Pennsylvania State University is extending the range of material options for MEMS made by a process known as microstereolithography. In a paper presented last fall at the Mechanical Engineering Congress in Nashville, the authors described 3-D ceramic structures with thicknesses of 50 microns to a millimeter, created by applying layer on layer of alumina ranging in thickness from 10 to 20 microns. One test structure included a ceramic band 5.7 micrometers wide and 10 thick.

The researchers also wrote that they have used the method to apply thick films, greater than 15 microns, composed of lead, zirconate, and titanate to silicon substrates.

The writers—Xiaoning Jiang, Cheng Sun, and Xiang Zhang—described the process as similar to the macro version of stereolithography for rapid prototyping. The primary difference was a couple of orders of magnitude in scale. They were using an ultraviolet laser that could focus as tight as 1 or 2 microns, as opposed to a beam that measures in the hundreds.

Fabrication using a laser guided by CAD files takes place at room temperature, without a cleanroom. Like the more familiar large-scale stereolithography, the micro version was originally developed for use with polymers, according to Zhang, who is the faculty member leading the research team.

As Zhang described it, microstereolithography "can expand the material spectrum to any material in powder form." The process can fabricate complex 3-D microstructures, such as a microcoil, he added.

Jiang, a postdoctoral student; Sun, a graduate student; and Zhang pointed out in their paper that the properties of ceramics, including piezoelectricity and resistance to high temperatures and chemicals, could be useful in complex 3-D microstructures for micromachines and fluidics. PZT thick films have played a role in sensors and
actuators with relatively high power output, as in micropumps and microtransducers, but current methods of manufacture lack the resolution of microstereolithography, the researchers said.

Zhang reminded an interviewer that the process is developed from rapid prototyping. He said the microstereolithography system can lay down 50 layers in 40 minutes. According to Zhang, “Microstereolithography offers robust CAD design and rapid prototyping features. One can make a part in an hour, and test it and go back to change it from CAD and try again.”

Currently, the technology turns out single pieces under an individual laser beam.

Since the paper was published, the research group has packed up its lab and moved to the University of California at Los Angeles, where their work is continuing.

There have been no commercial tests of the technology, but Zhang said that the group is recruiting commercial partners.

**INSPIRED BY RP**

The University of Southern California’s fabrication process also takes its inspiration from rapid prototyping. EFAB builds microdevices by stacking thin layers, each typically between 5 and 10 microns deep, creating as many as needed to complete a part. The process builds up cross sections until the part is defined. USC engineers have applied EFAB to fabricate a metal chain 290 microns wide. All of its joints are articulated. Instead of assembling the chain one link at a time, the fabrication technique made the 14-link chain in a single process.

Software has been developed to convert 3-D computer-aided-design files to a cross-section 2-D layout that calculates the design for each layer, and the developers are debugging a fully automated EFAB machine and finishing software to control it. Although the developers have a manually operating desktop system, fully integrating the automated system will take another couple of months.

“To build three-dimensional shapes as complex as those you find in rapid prototyping, you need to be able to put down hundreds or thousands of layers,” Cohen said. “Such complexity is just not possible with surface micromachining, which now is limited to five layers that require complicated processing. The higher level of complexity that you get with EFAB makes your job as a designer so much easier.”

Cohen predicts that, by the time they have finished their work, the developers will have a process that’s far more accessible to mechanical engineers than other MEMS fabrication systems. Cohen’s reasoning is that most of the other current MEMS processes have little connection to what mechanical engineers are used to dealing with. Cleanrooms and devices the size of transistors are generally not their domain.

EFAB, on the other hand, is intended to interface with standard 3-D CAD software such as Pro/Engineer or Solidworks.

**ADVANCING COMMERCIALIZATION**

EFAB is being developed by USC’s Information Sciences Institute with funding from the Defense Advanced Research Projects Agency. Some early work was contributed by the university’s Department of Materials Science & Engineering.

To support commercialization of the process, the Institute has established the EFAB Consortium, which intends to give interested partners the option of acquiring prototype microdevices fabricated from their own 3-D CAD designs. According to Cohen, the group hopes to begin the first fabrications in about five months.

Already the developers have a couple of organizations interested in developing applications for the new process. One is the Naval Air Warfare Center in China Lake, Calif., and the second is a company whose name was not released. The consortium is open, at a price of $30,000, to U.S. companies having more than 500 employees. Smaller U.S. companies, with fewer than 500 employees, can join for $20,000. U.S. companies with fewer than 100 employees, nonprofit concerns, universities, and government laboratories will pay $10,000 for membership.

The developers are licensing EFAB and expect to introduce commercial machinery and services in two to three years.

In the end, it may not be innovation that plays the most important part in deciding the success of MEMS techniques. Proving reliability may be just as important as producing impressive prototypes.

“Reliability is the single most significant challenge in the way of commercializing a MEMS process,” said Roger Grace, who runs Roger Grace Associates, a technology marketing consulting company in San Francisco. Market development and understanding the needs of the marketplace will also play a leading role, he added.