mechanical engineering



feature article

FEATURE FOCUS: *Next-Generation Materials*

# beyond silicon

## Engineers are expanding their material world to reduce the cost and tailor performance of microdevices.

by John DeGaspari, Associate Editor

Microelectromechanical systems evolved from the semiconductor industry, and silicon accounts for the vast majority of MEMS. That's no surprise, since silicon lends itself well to semiconductor processing, and the designers and engineers of integrated circuits and MEMS understand the material's characteristics and how to process it.

Yet when it comes to tiny electromechanical devices, silicon is not necessarily the best material choice in all applications. In fact, engineers have been steadily expanding the list of materials to work with, as techniques to fabricate MEMS components are becoming more refined. The result is that those working in MEMS have a bigger toolbox of materials at their disposal. And they are dipping into that toolbox as they try to bring new capabilities to the products they create.

For example, take bioMEMS, an area of huge potential growth driven by the surges in drug development, genomic research, and medical diagnosis. Roger Grace, a marketing consultant based in Naples, Fla., said these devices deliver on performance, but in many cases are still too expensive to be produced in very high volumes. In his view, this is at least partly due to an over-reliance on silicon in certain applications where better material alternatives exist. Microfluidic MEMS is one example. Silicon will continue to be used where there is a need for on-chip sensing because of its conductivity, but polymers are cheaper, more easily formed, and may be fine for channels that convey fluid from one part of a chip to another. There is a whole portfolio of alternative materials that MEMS engineers should be aware of, he said.

The focus on non-silicon materials has been coupled with "micro" refinements in traditional mechanical forming techniques, such as stamping, forming, and toolmaking. Some MEMS suppliers are experimenting with plastics by injection molding. Hot embossing, a technique to stamp finely detailed microfeatures in thermoplastic, is gaining use as well. The LIGA process, with its ability to produce detailed, high-aspect-ratio structures, is being applied to a growing list of metal alloys that could be enlisted as tooling materials to form polymeric parts. LIGA is a process that uses X-ray, lithography, and electroplating to produce highly detailed microscale metal parts. On a separate front, researchers have begun to look at bulk micromachined titanium as an alternative to silicon wafers.

## Think Plastics

Michael Huff is founder and director of the MEMS and Nanotechnology Exchange, a provider of foundry and consulting services in Reston, Va. A decade ago, while at Baxter Healthcare Corp. in Chicago, Huff applied MEMS technology to medical devices. "We didn't have polymers to use then; it was all silicon-based," he said. "For traditional microfluidics, I would have loved to have had the polymer-based technologies that exist now and have an order of magnitude lower cost."

Huff believes that the costs associated with silicon and micromachining were high enough to keep MEMS out of certain applications. He thinks that advances in fabrication techniques and the ability to form microstructures out of plastics will open up new opportunities for MEMS. Recently, he invested in a hot embossing tool to do process development with his customers.

Liwei Lin, a professor of mechanical engineering at the University of California, Berkeley, and chair of ASME's Microelectromechanical Systems Division, sees a role for plastic in microfluidic structures, and said that it offers advantages in biocompatibility. In his lab, Lin has produced a microneedle that will be combined with an on-chip blood-test system. He produced the needle, which has a diameter of about 100 micrometers, of Topas cyclic olefin copolymer, an engineering thermoplastic supplied by Ticona GmbH, of Kelsterbach, Germany. The micro-needle was produced in an aluminum mold on a standard 30-ton injection-molding machine. A graphite-based dry mold release was used to ease part removal.

One example of a commercial polymeric microfluidic device comes from Agilent Technologies in Palo

*Borrowing an idea from inkjet microfluidic technology, Agilent Technologies uses laser ablation to create microfluidic channels in its HPLC-Chip.*

Alto, Calif. Kevin Killeen, project manager of the company's microfluidics and biosensors group, said his team designed a microfluidic device based on Kapton polyimide film. Supplied by DuPont Electronic Technologies Business Group in Research Triangle Park, N.C., it is an engineering thermoplastic widely used in electrical and electronics applications as a flexible insulator. Killeen said the material has high chemical purity that can be used to separate compounds such as proteins and peptides for analysis. The device, called the HPLC-Chip, is smaller than a credit card and carries out liquid chromatography; it is mounted on a mass spectrometer to do the analysis.

The highly crystalline structure of the polyimide makes it resistant to solvents, Killeen said. He said the polymeric microfluidic channels eliminate many of the traditional fittings and connections, and reduce the possibility of leaks and dead volumes compared with microfluidic channels in fused silica glass tubing. Glass tubing is a conventional material that is more labor-intensive to work with.

Killeen said that the idea of using polyimide dated from the mid-1990s, when Agilent was still part of Hewlett-Packard, which uses polyimide in its inkjet printer heads. After the company spun off its laboratory equipment business and Agilent was formed, Killeen pursued the idea of using polyimide for medical diagnostic devices.

The polyimide film that holds the channels is patterned with a laser ablation technique, in which the film is laid flat and moved in relation to an optical beam of an intensity that vaporizes the material to form channels. "By controlling and focusing the intensity of the beam, we can change the depth and width and features of the channel," he said. Laser ablation is also used to form an integrated conical electrospray tip. The Kapton film is supplied in a roll, in thicknesses from 50 to 125 micrometers.

## Molding and Stamping

Steve Lesefko is vice president of engineering at Biosite Inc., a San Diego manufacturer of medical diagnostic instruments. The company's products include microfluidic devices with capillaries in the 30- to 40-micrometer range to perform immunoassays. The microfluidic devices use capillary action to move fluids passively.

Lesefko said that, after the company investigated various fabrication techniques for its microfluidic devices, it settled on injection molding to produce microfluidic parts molded of a styrene-based plastic. Lesefko said Biosite contracted with a micro-injection molder for production, but maintains tight control over the process. The molder makes parts on dedicated injection presses. During molding, machine parameters are checked once an hour and part dimensions are checked during each shift. After the microfluidic devices are molded, the parts go through post-processing steps in which channel surfaces are treated to either retard or increase flow, he said.

The parts are produced in multicavity steel molds that are able to hold tolerances through millions of cycles, he said. To assure quality, tools are periodically returned to the moldmaker to have the dimensions checked. According to Lesefko, the first injection mold produced for the company, in 1995, is still in service; he estimated that it has gone through 10 million cycles.


*A polyethylene micromolded part produced by Miniature Tool & Die has a pair of 75-micrometer slots. Plastic was fed through 50-micrometer gates.*

A micro-injection molder in Charlton, Mass., Miniature Tool & Die, has been in the business of making miniature parts for three decades, but has been producing micro- parts only for the past seven years—three of which have been in the MEMS area.

MTD defines microparts as components using a small portion of a plastic pellet, weighing fractions of a gram and having wall thicknesses of 100 micrometers or geometries that require a microscope for viewing. The company also makes the micro-injection molds that form microplastic parts for MEMS devices.

Donna Bibber, who is the company's sales and marketing vice president as well as a plastics engineer, said that plastic MEMS components are generally molded of polycarbonate, cyclic olefin copolymer, and polymethyl methacrylate, or acrylic.

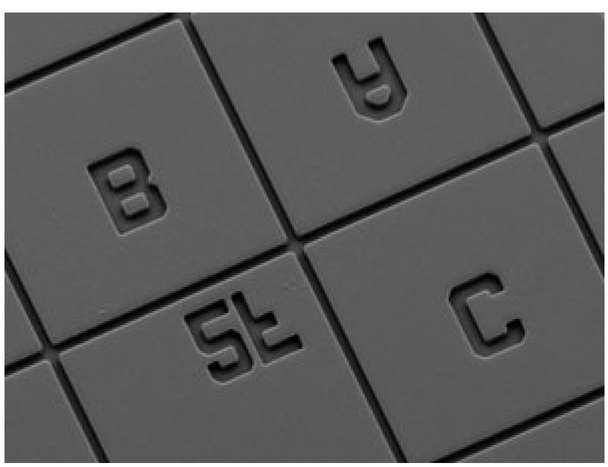
The number of channels in microfluidic arrays has been steadily increasing. Bibber said today's devices hold up to 3,456 channels on a 3 1/2- x 5-inch footprint. In the late 1980s, the first generation of these devices had only 96 channels in the same area, she said. Injection-molded parts fall into two broad groups—either microparts or macroscale parts with microfeatures. The smallest parts are very small indeed—the company claims to have molded 520 plastic parts from a single plastic pellet. Injection pressures can reach as high as high 35,000 pounds per square inch to force plastic through gates as small as 50 to 75 micrometers into the mold cavity.

Bibber said the molder developed its own flow analysis software to predict mold filling specifically for micro- parts. She said the company has scaled down the tests it needs to measure tensile strength of microparts and processing characteristics for micromolding. One test, called spiral flow, injects a resin sample into a spiral mold to see how it will behave.

According to Bibber, making molds for MEMS parts uses a combination of versions of standard techniques, such as electrodischarge machining and milling, and processes newer to moldmaking, such as LIGA, which she said is useful in producing flat and precise geometries.

Hot embossing is a competitive technique that is used to produce finely replicated plastic shapes into components such as microfluidic chambers, filters, and mixers. Johannes Fröhling, director of marketing and sales at Jenoptik Mikrotechnik GmbH in Jena, Germany, said that the company's equipment is flexible enough to mold structures as fine as 30 nanometers up to several hundred micrometers. The equipment can produce forces up to 200 kN, or about 45,000 pounds, and temperatures as high as 500°C, he said.

Essentially a sophisticated stamping process, hot embossing heats the polymer close to, or slightly higher than, its glass transition temperature, which is basically the point where an amorphous polymer changes from hard to soft.




*Hot embossing is used to imprint microscale structures in thermoplastics. A biomedical device* *like this one can have channels 10 micrometers wide.*

When the tool first contacts the polymer, it heats it above its glass transition point. A second force is applied to press the tool into the polymer. After a cooling phase, a demolding process occurs. Fröhling said the temperature between the tool and plastic substrate are closely matched during cooling to avoid thermal deformation of the plastic part.

Air or nitrogen is introduced into the gap as the tool and plastic separate. Fröhling claimed that this reduces the mechanical stress on the plastic as the tool is removed. Mechanical force is applied vertically during de-embossing to avoid additional strain on the structure.

Fröhling said that acrylic, which is relatively inexpensive and has a low glass transition temperature, is often used in process development. Cyclic olefin copolymer, which has high temperature stability and good optical properties, is being used more in MEMS applications. Because of its relatively high glass transition temperature, COCs are suitable for use in polychain reaction devices, in which temperature is applied to separate DNA for analysis, he said.

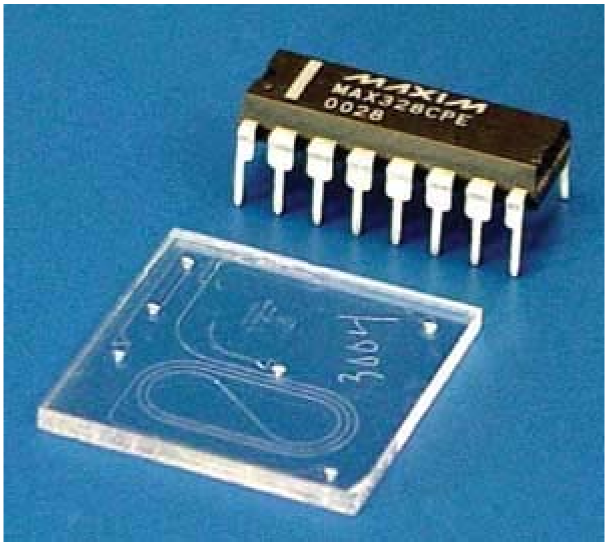
Various toolmaking techniques have been applied to stamping faces. Silicon tools can be used and are recommended for low aspect ratios. Metal tools, produced by milling, can hold geometries with high aspect ratios and are fairly inexpensive, but have high surface roughness. LIGA can produce parts with high aspect ratios and smooth surfaces. Tooling surfaces can also be made from glass.

Jenoptik is working on a next generation of embossing equipment that uses ultraviolet light rather than heat to form a part. He said that UV embossing would be useful in producing structures in several layers.

## LIGA Steps Up

Axsun Technologies, a micro-optical instrument company with a LIGA foundry in Livermore, Calif., licensed LIGA technology from Sandia to form intricate parts of metal. In the traditional LIGA process, X-rays bombard a photoresist on a silicon substrate, creating precise micro-cavities in the shape of the parts that are desired. The developed wafer is then placed in an electroplating bath, filling the cavities with nickel, copper, or other metals. The surfaces of the metal part are finished and the photoresist is dissolved, leaving the finished parts. The process can be applied to form tools for injection molding or hot embossing of plastic.

Starting initially with nickel, Axsun has expanded its capabilities to produce microscale components from a range of other metal alloys. John Rasmussen, director of government programs at the company, said that the availability of nanopowders has increased the types of metal that can be formed with the process.




*Microfluidic channels used in lab-on-a-chip instruments are etched in glass. Sandia National Labs may migrate to plastic in certain applications.*

Nanopowders are used in a lost-core type process. The powder is mixed with a polymer binder and then sintered to make the finished components. Rasmussen said that Axsun, working with Sandia National Laboratories, has used nanopowders to create parts of stainless steel and aluminum oxide, a ceramic. "We are probably only limited by the availability of nanopowders for the right material," he said.

Glenn Kubiak, deputy director of microsystems science and technologies at Sandia National Laboratories in Livermore, Calif., said that, while the laboratory continues to emphasize silicon for MEMS applications, it has also looked at alternative materials in recent years. He said Sandia typically has used etched glass in microfluidic components that go into its lab-on-a-chip instruments, but that the lab is making the transition to plastic because it is cheaper.

## Titanium MEMS

Researchers at the University of California, Santa Barbara, meanwhile, are investigating the use of titanium as a wafer material for MEMS. Noel MacDonald, who heads the research group, said that titanium has advantages over silicon with regard to packaging, material properties, and the ability to create three-dimensional structures. It is naturally shock resistant.

"The nice thing about titanium wafers is that you can throw them against the wall and they will survive," MacDonald said. This could help lower packaging costs compared to silicon MEMS that may require expensive packaging to protect against shock. Other desirable properties are that titanium is nonmagnetic, stands up to harsh environments, and is biocompatible, he said.

MacDonald said he finds that titanium has more flexibility in fabrication and is easier to make into three-dimensional structures than silicon. It can be machined, stamped, and formed with a laser, and can be bonded more easily than silicon, which tends to crack. "All of these things are available because the titanium infrastructure solved all of those problems," he said.

MacDonald said that titanium oxide, a natural semiconductor that is grown on titanium, also has potential applications for MEMS. It is a nanoporous material that has a large surface-to-volume area. It is a catalyst and has been made into photocells, and is biologically friendly. Recently, a student in MacDonald's lab developed crack-free titanium oxide structures, overcoming a problem of cracking that had kept it out of many MEMS applications, MacDonald said.

MacDonald is developing potential uses for titanium in his lab. He has used it to create micro-mirror arrays. He said that the ability to form titanium easily into three-dimensional structures makes it a good choice of material for bioMEMS and microfluidic structures.

Silicon is sure to be a material of choice among MEMS designers for a long time. But the availability of new materials, both for MEMS themselves and tooling to form microstructures, will open doors for new applications.