Suddenly, micromachines are positively, absolutely, utterly, incredibly, undeniably, almost magically . . . everywhere

by Alan S. Brown

As microelectromechanical systems (MEMS) step into the mainstream, they promise to change everything from television sets and cell phones to laboratory diagnostics.

With screens measuring five feet along the diagonal, Hewlett-Packard, Mitsubishi, Samsung, and Toshiba make some of the largest and most realistic rear-projection high-definition television (HDTV) sets on the market. The next time you pass one, stop and consider this: the picture you see is controlled by one of the most complex mechanical devices ever made.

Behind the screen lies a Digital Light Processor (DLP) from Dallas-based Texas Instruments Inc. (TI). Although only .65 inches on a side, TI's DLP contains more than two-million individually hinged and digitally activated mirrors, each one-fifth the width of a human hair.

Each mirror has only one job, to shine a ray of light on a single pixel of the HDTV's screen. To produce an image, the television set shines a beam of light through a rapidly rotating wheel containing red, blue, and green color filters. When the colored light strikes the DLP, each mirror reflects it onto or away from the screen.

To produce a pure blue pixel, the mirror steers only light coming through the blue filter onto the screen. Reflecting all the blue light onto the screen yields a very intense color; bouncing some light away from the screen produces a more washed out tint.

The mirrors also mix colors. To show the sea, for example, a mirror directs both blue and green light onto a pixel. The mirror turns light on and off so quickly—up to 62,500 times per second—that our eyes blend the colors together into sea green. By controlling color blending and intensity, each tiny mirror can project up to 16.7 million different colors.

MEMS

TI's DLP is just one of a new wave of microelectromechanical systems (MEMS) that have begun to appear on mainstream consumer products. MEMS comprise the read/write heads on hard drives and the print heads in inkjet printers. They are the accelerometers that launch airbags within milliseconds of an accident and safely park hard drives before a dropped laptop hits the floor.

MEMS gyros steady digital cameras and help global positioning systems (GPS) remember their locations when they lose their satellite connections. MEMS pressure sensors regulate air-fuel mixing in auto engines and measure arterial pressure during surgical procedures. They make cell-phone microphones smaller and enable lab-on-a-chip biological testing. MEMS resonators promise to replace quartz crystals as

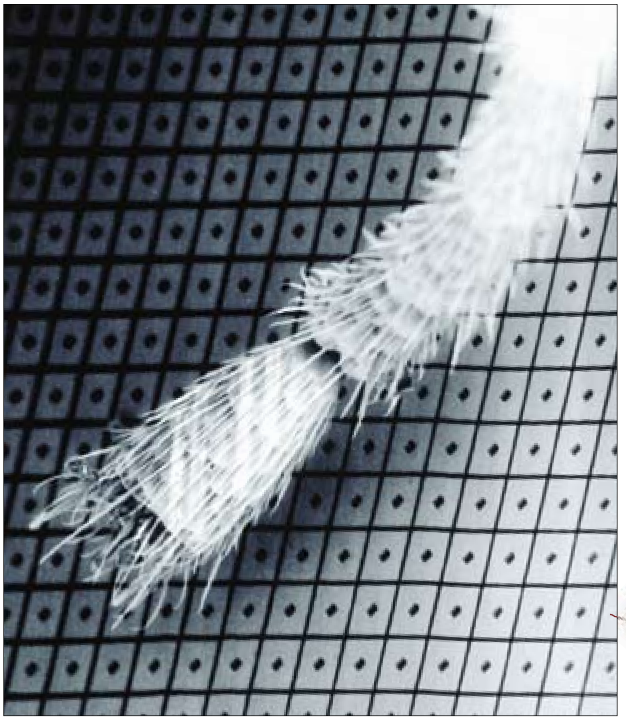
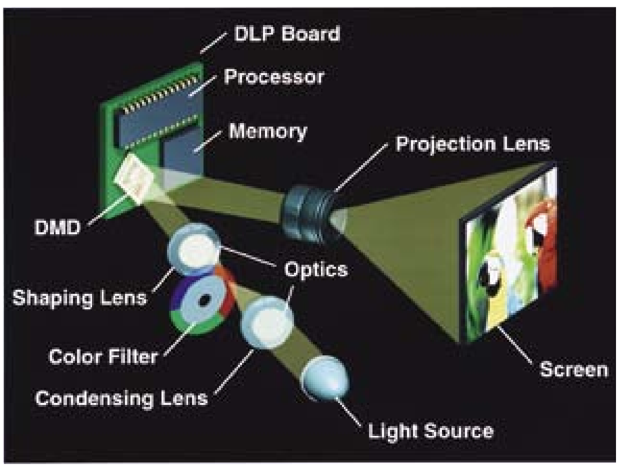


Figure 1 Micrographic photo of an ant leg on Motorola digital-light-processor mirrors. Each mirror is 16-microns square, with a one-micron separation between mirrors.



All figures courtesy of Motorola

Figure 2 White light shines through a spinning wheel with red, green, and blue filters and onto the Motorola digital light processor. Mirrors are turned on, depending on where and how much of each color is needed for each TV pixel. Human eyes integrate the sequential color and see a full-color image.

time keepers on digital devices.

MEMS are quietly changing our world, sensing and actuating in ways that go far beyond the capabilities of electronic circuits alone. Their very name, microelectromechanical systems, describes their fusion of moving elements with electronics to control or sense motion. Most are built on silicon wafers using such semiconductor processes as sequential deposition, patterning, and etching.

A MEMS accelerometer, for example, might consist of two comb-like structures (Fig. 5) whose interleaved tines are suspended over a cavity in a silicon chip. Current runs through the combs. As changes in motion deform the structure, the distance between the combs changes and alters its capacitance. Measuring those changes yields acceleration.

Yet the very definition of MEMS continues to expand. While most MEMS are made from silicon using semiconductor processes, others are molded from plastic or etched into glass or titanium. Some, like hard drive read/write heads and labs-on-a-chip, have micron-scale features but no moving parts. The MEMS-based printer head developed by Hewlett-Packard Company of Palo Alto, CA, which uses a resistor to heat ink until mounting vapor pressure propels it out the orifice.

Figure 3 Nine Motorola digital-light-processor mirrors—with the central mirror removed to expose the underlying hidden-hinge structure.

Figure 4 An enlarged view reveals the mirror substructure and the post that connects to the mirror in the center.

All figures courtesy of Motorola

Economics

MEMS are already a big business. In December 2005, a study by Germany's Wicht Technologie Consulting valued the market at nearly $15 billion, about three quarters in read/write heads, microdisplays, and inkjet heads.

The tiny devices have a disproportionate economic impact, says Ellen McDevitt, executive director of the Pittsburgh-based MEMS Industry Group, which represents MEMS developers. "Our members are at the beginning of the value-added food chain," she explains. "A printer head might cost a few dollars, but the print cartridges that contain those heads sell for many times that." A survey of organization members found MEMS-based products sell for 10 to 50 times the price of the MEMS itself.

Because MEMS are made by semiconductor processes, producers are able to crunch down costs just as chipmakers have done in the past. They are squeezing more ever-smaller sensors onto ever-larger wafers while raising yields. Startup SiTime Corp. of Sunnyvale, CA, for example, fits 50,000 MEMS-based resonators on a single eight-inch wafer. Even though it spends thousands of dollars processing each wafer, it produces so many resonators at a time that it can sell each one for as little as $0.40 and still make a profit.

Long-time MEMS market guru Roger Grace of Naples, FL, underscores the importance of slashing costs. "MEMS are true OEM [original equipment manufacturer] products," he says, referring to components used to build products for end-users. "If you're an automotive MEMS supplier, you have to knock five percent off the price to get the deal," says Grace. "But it's not a one-night stand. You need to reduce the price five percent every year. Price is incredibly important to get into large volume consumer applications."

Many MEMS makers are already learning this lesson. Four years ago, Grace bought a DLP-based presentation projector for $3,500. Today it sells for less than $1,000.

As prices go down, volume goes up. As DLP Products program manager Mike Mignardi notes, TI sold its first true DLP chips in 1996. In 2001, it sold its milionth MEMS. Five years later, it sold its ten millionth DLP. "That's hockey stick growth," says Mignardi. Now that same type of growth is starting to happen across the entire industry.

Mirrors

Rapid growth did not come easily. It took nearly 20 years for DLPs to take off. "When I joined TI in 1989, the term 'MEMS' didn't even exist in our lingo," says Mignardi. "We didn't even know what MEMS meant until we started attending meetings."

Mignardi joined TI two years after company researcher Larry Hornbeck had the idea of hinged mirrors. At the time, he was creating thin-film diaphragms and deforming them to generate constructive and destructive interferences with light. The diaphragms proved hard to produce reliably, and his team threw away entire wafers without salvaging a single working device.

"Larry decided he needed something more stable, and he came up with the idea of a thicker hinged mirror that could tilt," Mignardi recalls. In 1987, Hornbeck made his first mirror array from an aluminum-based alloy applied by semiconductor methods to a standard polycrystalline silicon wafer.

It took three more years to reach production. Along the way, TI's engineers had to solve some complex issues. They had to learn how to carve deep air gaps under the MEMS mirrors and etch the metal layer into complex hinges and reflective surfaces. Separating the mirrors from one another

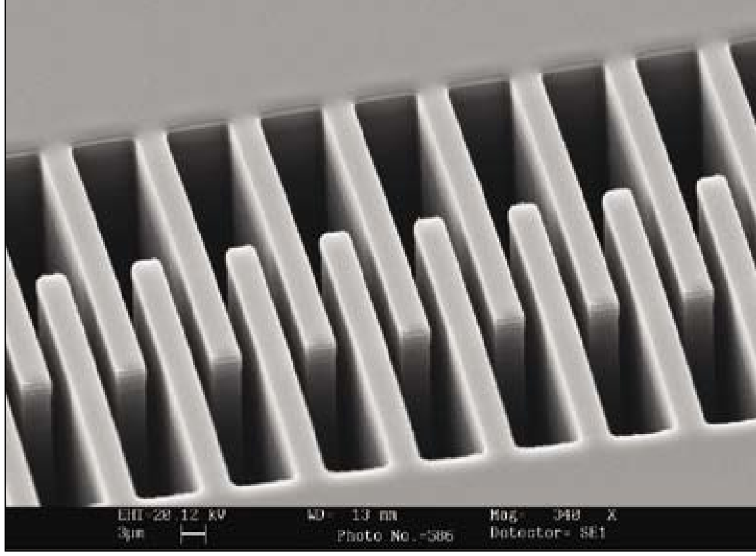


Figure 5 Comb drives are often used in accelerometers to activate air bags or protect a laptop hard drive if dropped. This electrostatically activated comb drive moves two optical fibers into alignment to route communications signals.

Images this page courtesy of Micralyne, Inc.

proved tricky, because conventional processing ripped them off the wafer.

Simply finding the equipment to build a prototype proved a challenge. Unlike semiconductors, which used a standardized set of materials and process sequences, mirrored MEMS required unusual process sequences.

"We had to make use of a lot of different wafer tools at different fabrication lines within TI," Mignardi recalls. "There was no centralized location where we could do everything. The same was true for testing and packaging. I remember coming in at three in the morning to get our testing done."

The team's first product was an airline-ticketing and boarding-pass printer head. Conventional printers used a laser to raster-scan one line of a xerographic drum at a time. TI's first chip had 840 mirrors and could steer light across the entire surface at once. Not only was it faster, but the MEMS used a less expensive tungsten-halogen bulb rather than a laser.

While working on the printer, TI researchers began thinking about using MEMS to project images onto a screen. Shortly after they launched the printer head, they packaged two mirrored MEMS into a crude optical benchtop. "We showed we could project pixels onto a screen with good color, clarity, and contrast ratio, and that the chip was robust," Mignardi recalls. "After that one demonstration, TI decided to invest in creating a projection-display business."

That was in 1992. The new digital-imaging venture-projects group spent the next four years making denser MEMS, building a manufacturing line, and proving product reliability. "We had no fundamental problems, like hinges breaking, but we had to prove to people outside TI that the hinges wouldn't break," Mignardi says. "We had to show them that moisture wouldn't get into the package and ruin the mirror."

In 1996, TI shipped its first imaging product. It featured more than 300,000 movable mirrors, enough to handle the output of a standard 640x480 pixel VGA computer display. The firm sold the MEMS to makers of projectors used to display presentations at meetings. It proved an instant hit, and TI still claims more than half of the projection market.

TI followed with an 800,000-mirror MEMS that offered higher projector resolution. Then came a set of three (one each for red, blue, and green) two-million-mirror DLPs for movie theaters that reproduce up to 35 trillion colors. HDTV DLPs soon followed.

Mignardi says he does not know how much money TI invested in DLP technology. Some analysts believe the number runs well into the hundreds of millions of dollars. Only now is the company generating the volume needed to recover its investment.

Hurdles

While TI was perfecting its DLP, other MEMS developers were getting ready for prime time. That meant surmounting a technology curve every bit as steep as the one faced by TI's DLP, says Allyson Hartzell, a MEMS reliability expert with Exponent/Failure Analysis Associates Inc. of Natick, MA.

MEMS, Hartzell explains, face the same physical forces—shock, vibration, heat—as larger mechanical parts. Those forces, however, play out differently on the micro level.

Take, for example, *stiction*, a term coined by the disk drive industry to describe static friction. It occurs when micron-scale parts touch and cling to one another. This is caused by van der Waals forces, a weak form of polar attraction between molecules. This force is rarely noticed on large parts. On MEMS, it can be a show stopper unless manufacturers treat parts with nanoscale lubricants and anti-stick coatings, says Hartzell.

Microcontamination poses even greater challenges. "It is critically important in terms of yield and reliability," says Hartzell. A single one-micron-diameter particle is enough to cause catastrophic failure if it wedges into a moving mechanism. Shock and vibration make the problem worse, because they can knock a particle into a critical location and cause sudden catastrophic failure. MEMS are vulnerable to moisture, which changes the surface energy of moving parts and causes stress-corrosion cracking. And MEMS mechanical performance changes with fluctuations in temperature.

MEMS developers responded in several ways, says Hartzell. They created ultra-clean processing rooms that limited microcontaminants to no more than one 0.5-micron-diameter particle per cubic foot. They packaged entire wafers with hermetic or semihermetic seals and developed proprietary ways to cut the small encapsulated MEMS from the wafer. To cushion against vibration, they attached MEMS to substrates with rubbery materials that absorbed shock. Electronics, either onboard the MEMS device or on a separate chip, compensated for temperature changes.

Profusion

"Ten or 15 years ago, a lot of folks said we couldn't do it," says Hartzell. Today, building on technical advances pioneered in the 1980s and 1990s, MEMS are moving into the mainstream.

Analog Devices Inc. of Cambridge, MA, and Germany's Robert Bosch GmbH, for example, produce MEMS accelerometers to activate airbags in milliseconds after an accident. Many of the 63 million cars manufactured worldwide use several accelerometers to manage their airbags. Analog Devices alone ships more than one million four-millimetersquare accelerometers each week and another one-million chip-sized gyroscopes for automotive airbags and suspensions every month.

Hewlett-Packard, which produces a significant share of the one-billion inkjet-printer cartridges sold annually, uses MEMS-based systems to apply ink. Several manufacturers make micro structured MEMS read/write heads for the 376 million hard drives sold in 2005. Many of the one-billion mobile phones expected to be sold in 2006 use MEMS-based microphones and MEMS gyros to stabilize pictures on built-in cameras.

Pressure sensors have made significant inroads among automakers, where they are used to measure everything from tire pressure to engine oil and power steering and braking fluids, says David Tietjen, vice president of sales and marketing for Merit Sensor Systems, Inc., of Santa Clara, CA. Merit specializes in piezoresistant pressure sensors, which measure the change in electrical resistance of a thin silicon diaphragm as it deforms under pressure. "Because of their cost, size, and robustness, MEMS are going to eventually go into all sorts of products we don't even think about today."

Bomb

Despite their technical and market success, MEMS have flown under the radar of venture capitalists for most of the past decade. "We face a dilemma," says MEMS Industry Group's McDevitt. "The mass market is hard for small companies to break into, and 40 percent to 50 percent of our members have fewer than 20 employees."

Funding MEMS ventures has been problematic since the MEMS meltdown after the dot.com bubble burst in 2001, says Bruce Alton. A longtime industry survivor, Alton is vice president of marketing and business development for Micralyne Inc., a foundry that makes MEMS for other companies.

In the late 1990s, recalls Alton, the Internet boom convinced telecommunications companies that they needed to invest in more signal-carrying capacity. Many had already laid more optical-fiber capacity than they could use. The problem lay in switching.

To send signals over fiber, telecom companies first had to convert digital signals into light. At the next switching station, they reconverted them back to digital, rerouted them, and then converted them back into light. Digital-optical switching could take place several times before the final signal reached a home or business.

Digital-optical switches are relatively slow and inefficient. More importantly, though, they forced companies to invest in two sets of switches, digital-to-optical and optical-to-digital, to route signals. MEMS developers, using mirror technology similar to that pioneered by TI, promised to eliminate the need for converters with all-optical switches.

The technology was barely out of the lab. Yet telecom suppliers—fueled by stock prices inflated by the dot.com boom—jumped on these start-ups. In 2000, JDS Uniphase Corp. acquired Cronos Integrated Microsystems Inc. for stock valued at $750 million at the time. Cronos, a lab-based spin-off, had been in business for just one year.

Other deals soon followed. Corning Inc. bought MEMS design-software developer Intellisense Software Corp. for $750 million in stock. Nortel Networks Corp. purchased Xros Inc. for $3.25 billion in stock (about $36 million for each of its 90 employees). Venture capitalists saw these valuations and couldn't wait to throw money at the next MEMS start-up. OMM Inc., for example, raised hundreds of millions in venture-capital funding.

It all came tumbling down. The dot.com bubble popped. Stock valuations fell. The nation slipped into a recession. Telecom companies stopped investing in capacity. MEMS firms smacked into technical barriers. JSD sold Cronos for pennies on the dollar. Corning closed Intellisense, then sold it back to its founders. OMM shuttered its doors.

"People underestimated what it would take to get a product to market," says Alton. "It gave all MEMS a bad name. Venture capitalists thought, 'If so many companies went out of business, the technology must be bad.' "

Five years later, though, optical switches account for "a significant amount" of Micralyne's fabrication business. "We grew 50 percent last year and expect to grow the same amount this year," says Alton. "The technology is very powerful, it works, and it's being implemented into the marketplace." Not surprisingly, the firm's customers do not emphasize the MEMS aspect of their offerings. Instead, they call them "optical switches" and focus on issues like increased throughput and lower costs.

Infrastructure

Micralyne's business underscores another change in MEMS since the 1990s: the growth of fabricators capable of manufacturing MEMS for smaller developers who cannot afford their own production lines. Such "fabless" production has been a fact of life in the semiconductor industry for decades.

The semiconductor uses one small set of materials and a fixed sequence of processes, so it is possible to create a strong set of design rules, Alton explains. MEMS developers, on the other hand, use many more materials and processes. Their devices have acoustic, optical, and physical as well as electronic interfaces. This makes it much harder to define standards.

Yet a growing infrastructure has begun to emerge. The U.S. Defense Advanced Research Projects Agency (DARPA), for example, funded the creation of Nanotechnology Exchange in Reston, VA, a virtual foundry that lets developers access MEMS processors around the country. Michael Huff, who runs it, says that the exchange does 40 to 50 projects weekly and that it processes the average MEMS at three different fabricating facilities.

IceMos Technologies Corp. of Tempe, AZ, is one of many companies looking to process MEMS. It produces specialized wafers that have single-crystal silicon surfaces, which are stronger and more easily controlled than conventional polycrystalline silicon, says vice president Raymond Wiley. The company can also etch very deep features into its wafers using a process called reactive ion etching. "That cuts out one to three steps for our customers and improves their yield," he says.

Wiley has seen vast changes in *fabless* processing. Originally, semiconductor fabricators did not want to handle MEMS. There were many reasons for this. MEMS volumes were low, and they required specialized device packaging and testing. More recently, though, industry suppliers like IceMos, which does most of its business with chip makers, have begun to offer MEMS capabilities. Other MEMS fabricators include major semiconductor firms like Taiwan Semiconductor Manufacturing Company Ltd. and Cypress Semiconductor Corporation.

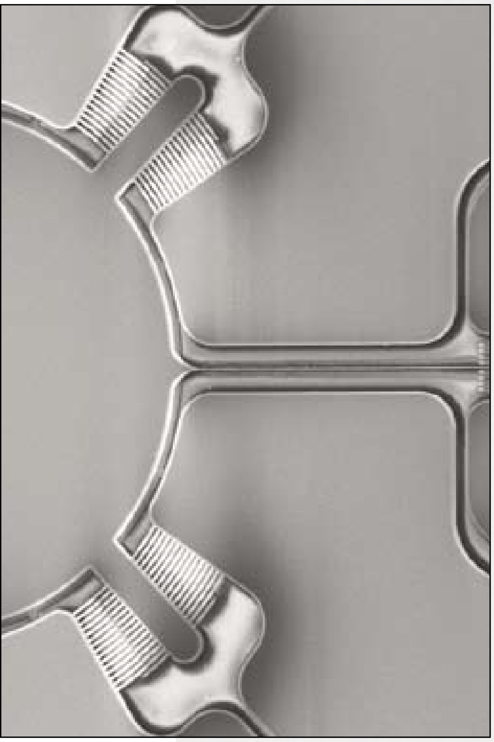


Figure 6 Two wafers bonded together create this optical mirror, whose motion switches reflect light from optical fiber to another. The comb drives in the U-shaped structures on the side of the mirror enable it to move left and right in a circular motion. The hinged structure on the left allows it to move up and down.

The Future

Fabless production promises to bring more MEMS applications into the mainstream. Yet for MEMS to truly compete in volume markets, they must be cheap. SiTime, whose founders include Dr. Kurt Petersen, *California Alpha '70*, who is considered the father of micromachining, shows how this can be done.

The company's product is a MEMS resonator, an electrostatically actuated silicon beam designed to vibrate at a specific frequency. Counting those vibrations lets chip electronics control the timing of digital switches in everything from PCs and mobile phones to video games and electronic door openers.

"In consumer electronics, cost is king," says Petersen. In this case, the reigning timing technology is quartz oscillators. To compete, SiTime must sell resonators for less than 50 cents/unit.

"This couldn't have been done five years ago," says Joe Brown, SiTime's head of strategic alliances. He says two keys have opened the door to making resonators competitive.

The first is semiconductor-production technology that enables SiTime to make features as small as 180 nanometers. This is 0.06% of the length of SiTime's 300-micron square resonator. It gives SiTime enough precision to fill a wafer with 50,000 resonators, all vibrating within a few parts per million of the same frequency.

A second critical technology ensures that SiTime's resonators remain perfectly tuned. This is a low-cost hermetic packaging developed by Bosch for accelerometers. It involves filling the finished resonator with a thin layer of silicon oxide and growing single-crystal silicon over it at 1,000ºC. SiTime then drills a small hole in each MEMS and bathes the wafer in acid to remove the oxide and free the resonator. It then plugs the hole under a vacuum, leaving behind a wafer of hermetically sealed resonators.

A small digital chip completes the device. It contains electronics that convert analog-resonator vibrations to digital signals and compensate for temperature changes. Attaching the chip to the top of the MEMS die completes the package.

The result is only 0.85 millimeters high. It uses only a fraction of the space required by quartz oscillators and their associated electronics. It is virtually immune to shock and vibration. SiTime plans to build the electronics and multiple resonators, all vibrating at different speeds, on a single chip that can replace several oscillators.

Petersen is optimistic about grabbing his share of the nine-billion unit, $3 billion quartz-oscillator market. He should be. He has a product that is just as precise, but smaller and cheaper. While SiTime's production process is not cheap, it can divide its cost among 50,000 resonators. As it learns to make smaller resonators and improve yields, it will push costs down still further. The semiconductor technology has been doing this for decades. MEMS are sure to follow.

It is a powerful formula. As MEMS become cheaper and prove their reliability, they will find their way into more and more consumer products. If MEMS resonators are cheap enough for inexpensive digital wristwatches, then tires that monitor their own pressure, implants that release medicine, and pocket GPS systems can't be far behind. One day we may see cell phones with their own weather stations, health diagnostics, and MEMS-powered fuel cells.

Ubiquitous MEMS promise to change the world in ways that are both unnoticed and startling.

Alan S. Brown has been an editor, contract editor, and freelance writer for more than 20 years and lives in Dayton, NJ (*insight@comcast.net*). A member of the National Association of Science Writers, he earned his B.A. *magna cum laude* at New College at Hofstra in 1974 and won a Phi Beta Kappa scholarship. He is executive editor of *Homeland Response,* contributing editor of *NASA Space Research* and *IEEE Spectrum,* and a regular contributor to *Mechanical Engineering*.