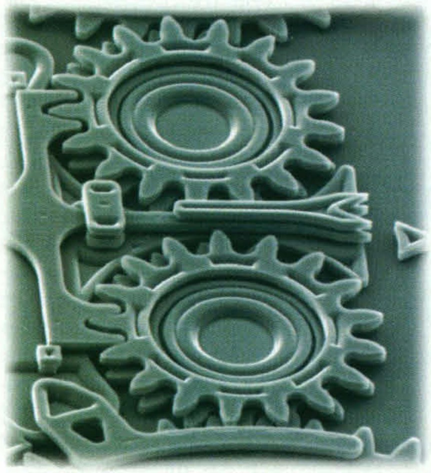
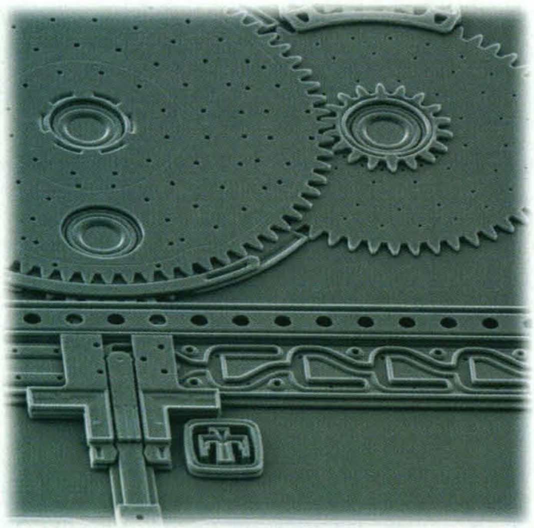
FUTURE CHIPS
MICROMACHINES

Fomenting a Revolution, in Miniature

A novelty a decade ago, microscopic machines are making gains in the marketplace and may be poised to become the darlings of Silicon Valley

With the passion of an evangelist, Karen Markus crisscrosses the globe to let everyone from university professors to corporate bigwigs in on her good news. MEMS, machines invisible to the naked eye, are primed to shake up the world of microelectronics, she says. Now is the time to jump on the bandwagon—or risk getting left behind. According to Markus, director of the MEMS program at MCNC, a publicly funded technology incubator in Research Triangle Park, North Carolina, MEMS—a.k.a. micro-electromechanical systems—"are going to be everywhere."





Small wonder. Sandia's intricate safety lock for nuclear missiles won MEMS design contest (right); closeup view of 50-micrometer gears.

Ranging from simple levers and rotors to complex accelerometers and locking systems for nuclear weapons, MEMS are fashioned largely from silicon with techniques adapted from the microchip industry. Think of MEMS as microelectronic chips that have taken an evolutionary deflection toward a new sub-Lilliputian species that not only can think like Pentium chips but also can sense the world and act upon it. "MEMS are enablers. They'll be all over, like plastic. They're viral. They will infiltrate everything," Markus says.

That message may be a bit unsettling to the uninitiated, but it resonates among specialists who have watched MEMS blossom in the last decade. The public was treated to its first glimpse of these devices in the late 1980s, when stunning pictures of tiny rotating gears and motors no larger than dust specks began appearing in the likes of *The New York Times* and *Business Week*. At the time, MEMS were more promise than reality; their moving parts tended to seize up in seconds or they curled like wood shavings into intriguing—but useless—microscrap. In the past few years, however, scientists say they have solved many of these bugaboos. Now, they claim, the ability to miniaturize mechanisms could well define the next technological age the way microelectronics has defined the present one. "There is a strong and growing consensus that [MEMS] will provide a new design technology having an impact on society to rival that of integrated circuits," says MEMS elder Richard S. Muller, co-director of the University of California's Berkeley Sensor and Actuator Center (BSAC).

The virtues of these tiny machines are many. MEMS are fast and generally cheap to mass-produce, at least after an R&D shop has hammered out a working design. And they boast startling mechanical sophistication in packages no bigger than a standard computer chip: Scientists have already moved MEMS into various stages of conception and development for making laboratories on chips, data-storage technologies, cell-manipulating gadgets, propulsion systems for microsatellites, locking mechanisms for nuclear weapons, and many other applications.

The wee machines have already caught the eyes of systems engineers, the technological arbiters who decide which components to put in new devices. Since 1993, for example, car air-bag systems have employed MEMS-based accelerometers. The MEMS part, made by Analog Devices Inc. of Wilmington, Massachusetts, and other firms, is a tiny chunk of silicon suspended in a cavity. Jutting from it are dozens of bristles, like centipede legs, that are interwoven with bristles extending from the cavity walls. The tiniest movements jiggle the chunk and change the interweaving, altering the structure's ability to store charge. A violent jarring results in voltage perturbations that trigger the system to deploy the air bag.

As MEMS carve a niche in today's markets, the ideas pipeline is surging, with an estimated 10,000 scientists and engineers—not to mention an army of product developers and marketers—keeping the valves open. Roger Grace, an engineer and consultant in Silicon Valley who has been promoting the emerging field for years, estimates that about 600 university, government, and private labs are working on MEMS devices worldwide. Fueling this enterprise is ample government support—the Defense Advanced Research Projects Agency (DARPA) alone spends $60 million a year on MEMS. Millions of dollars of venture capital are pouring into the field, and the resulting start-ups are getting snatched up by larger companies. Graduate students have been clamoring to get into MEMS programs, then starting up their own firms even before getting their diplomas. "There is a gold rush atmosphere here," says Roger Howe, MEMS pioneer and BSAC co-director.

Lurking in the shadows of this mountain of promise, however, are profound concerns that nag even the field's biggest boosters. "There are phenomenal ethical dilemmas in the making," says Markus, arising from the power of MEMS devices to see, hear, feel, and taste—as well as their ability to record and transmit observations. Insiders whisper about "smart dust," or MEMS particles equipped with sensors, processors, and communications elements that could monitor people and places and report back what they sense, putting to shame the tools of today's spy masters. "The incredible surveillance ability means that privacy could become a scarce commodity," at least if the technology is put to sinister uses, Markus warns.

Such issues have yet to be addressed sub-

CREDIT: SANDIA NATIONAL LABS

stantially by the community, which for now is preoccupied with maintaining—and building—its momentum. Adherents say MEMS is at a place now where integrated circuits were in 1972: on the launch pad and ready for takeoff. Says Howe, "It's a fantastic time."

The report heard 'round the world

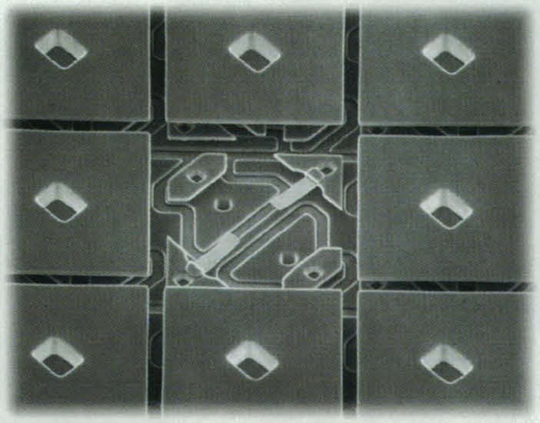
The field of MEMS emerged from several lines of inquiry that began to converge in the 1960s and 1970s. Nurturing the infant field were iconoclasts who challenged the direction in which microelectronics was heading. Among them was Kurt Petersen, who recently co-founded Cepheid, a Silicon Valley company with a mission to create chip-sized analytical laboratories from MEMS and other microtechnologies (see p. 399). In 1975, Petersen arrived at IBM's Research Laboratory in San Jose, California, with an electrical engineering degree from the Massachusetts Institute of Technology, virtually guaranteeing him a front seat in the microelectronics revolution.

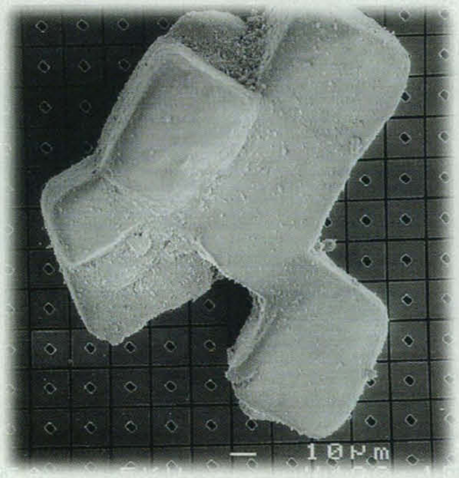
But it wasn't electronic devices that intrigued Petersen, whose background was in integrated circuits. "I was fascinated when I saw them using this process for making ink-jet nozzles" for printers, he recalls. Using a combination of two techniques—photolithography-based tools for engraving microscopic circuitry in a silicon wafer, and acid etching, which eats patterns in a wafer according to the orientation of its silicon crystals—the IBM researchers were able to sculpt miniature structures, including precisely shaped nozzles that directed hot puffs of ink onto paper with enough precision to match the performance of a metal typeface.

The nozzles, each smaller than a pinhead, were amazing, all right. But it wasn't the flawless performance of well-machined nozzles that kindled Petersen's imagination. "I was looking at the ones with mistakes in them," he says. Under a microscope, he saw beams, bridges, and other minuscule structures. To Petersen, these aberrations offered a glimpse into a hidden world of possibilities. "I got excited about the whole issue of making mechanical devices on silicon," he says.

Pleased by Petersen's spark, his bosses gave him his own lab to test silicon's micromechanical mettle. First Petersen scoured the literature for kindred spirits. "I found there was a whole technology out there, but none of the people involved knew of the others," he recalls. Figuring he was onto something, he spread the word about silicon's untapped riches to IBM colleagues in a confidential internal report in 1981.

Next, Petersen took a watershed step: He published a version of the internal report in the May 1982 *Proceedings of the Institute of Electrical and Electronics Engineers*. The first sentence said it all: "In the same way that silicon has revolutionized the way we think about electronics, this versatile material is now in the process of altering conventional perceptions of miniature mechanical devices and components." That message circled the globe and in short order had turned





Who's the smallest of them all? Sugar crystal dwarfs dozens of micromirrors in Texas Instruments' MEMS computer display; removing a mirror reveals the levers behind *(top)*.

CREDITS: TEXAS INSTRUMENTS DLP

silicon from a celebrity of the microelectronics revolution into a darling of the budding micromachine movement.

By the end of the 1980s, this movement was bursting out of the insular world of research, thanks mainly to the Tom Thumb appeal of microscopic wheels and rotors, which regularly landed MEMS in the news. The field rode its cuteness factor for years, says Markus. But a whimsical reputation was threatening to sap the MEMS momentum. "Bedbugs on merry-go-rounds trivialize things," Markus says, especially if you don't start making devices people can use. Researchers were churning out mechanical wonders in the lab that would never earn their keep.

It would take a few bold companies to transform MEMS from toys into products. First, they had to overcome key technical challenges in carving minuscule, but intricate, patterns in silicon. For example, the complex procedure for patterning shapes like gears onto silicon substrates and then etching them into freely moving parts often left residual strains that reduced a device's durability; researchers overcame this by such means as adding an hourlong annealing step that makes the silicon crystal structure especially uniform and thus relatively free of internal strain. Proving that MEMS are marketable were products such as the air-bag accelerometers, which hit the market about 5 years ago, and more recently the Digital Micromirror Display—a computer screen made by Texas Instruments (TI) in which a million or more swiveling mirrors etched onto a MEMS chip blend the three primary colors—red, green, and blue light—to convert electronic photo or video files into high-resolution images. These first fruits, says Petersen, "gave the field the credibility it needed."

Storing data, locking nukes

Now that MEMS are on the shopping lists of the systems folks who figure out how to assemble technology into complicated devices such as bar-code scanners, fax machines, and automated teller machines, the doors are open for an invasion of MEMS into the technoscape.

Take Quinta Corp., a 2-year-old firm caught up in the industrywide chase to pack more data into disk drives. Its researchers hope to multiply disk storage density by incorporating MEMS devices into Winchester technology, the standard rotating hard-disk drive systems in most PCs. In these disks, data are stored in concentric tracks—high-end machines pack as many as 4000 lines per centimeter. MEMS, predicts Quinta co-founder Joseph Davis, will boost that to 40,000.

The central challenge is to find a way to keep the magnetic head, which reads and writes data, trained on much narrower tracks. Even in today's best drives, the actuators that keep the head on course have nothing like the needed finesse, says Davis. "The only way to go to the next level," he says, "is to come up with a secondary device that rides on the actuator and enables you to move the head onto the right track"—a kind of coxswain, that is. "This is where MEMS come in."

Davis had in mind a laser guidance system that would force the head to stick to the skinnier tracks. He set out to try MEMS after a colleague faxed him an article about TI's micromirrors, which had proven adept at rapid, precise maneuvering. Quinta's twist was to design an "analog mirror" that rotates to many positions, compared to TI's "digital" mirror, which assumes only two positions.

Here's how the system under development works: After an actuator brings the head to within 10 tracks of the target, a solid-state laser shoots a beam through optical fibers spanning the actuator's length. A MEMS mirror deflects the beam downward through a lens that focuses light onto the disk's surface. The mirror's position dictates which track the light will strike. If the laser beam strays off course, reflections from pits flanking the track light up photodetectors, which feed back into the magnetic head's control circuitry. "Without MEMS technology, we could not do what we are doing," says Quinta's Phil Montero. Data-storage giant Seagate Technology Inc. of Scotts Valley, California, would seem to agree: It acquired Quinta last year for $320 million.

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—Karen Markus

Better data storage is no small prize in this information age, but technologies for preventing nuclear weapons from detonating accidentally command a greater sense of urgency. "Our goal is to enhance the security for nuclear weapons," says Paul McWhorter, director of a multimillion-dollar MEMS program at Sandia National Laboratories in Albuquerque, New Mexico. Not that today's fist-sized security systems are problematic, he hastens to add, but MEMS have some potential advantages. For one thing, "micromachines, just by being small, are more rugged," McWhorter says. They can take a beating without failing. What's more, he says, the space saved by MEMS-based systems opens up precious real estate inside the tightly packed control units of nuclear weapons. That can allow designers to add instruments that might, for example, improve the accuracy of missile targeting.

To reap these benefits, Sandia's Steve Rogers has created what many experts tout as the most complex MEMS ever made: a locking device whose creation required 14 photolithographic masks and more than 240 processing steps similar to those required to forge integrated circuits. McWhorter hopes the prototype will evolve into a device that prevents "abnormal events"—such as fires, plane crashes, or terrorist bombings—from leading to weapons becoming armed.

Rogers's Rube Goldberg machine writ small has won kudos from his peers, including a grand prize from the engineering magazine *Design News*. It responds to a 24-bit computer code that specifies the unlocking sequence. Each bit is a command for a pin, the size of a red blood cell, that fits into a linear maze etched on a microscopic gear. As the gear rotates, the pin must go up or down at turns in the maze. Given the correct bit, the pin takes the turn that allows it to proceed to the next turn. Given the wrong bit, the pin hits a dead end, which blocks the rest of the unlocking sequence and keeps the weapon locked and disarmed.

If the pin successfully navigates all 24 turns, a second mechanism kicks in that pops micromachined mirrors up from the surface of the silicon-based device. After that, conventional technology kicks in: The mirror shunts a laser beam to circuitry that arms the weapon. The whole device, says McWhorter, "looks like a speck" to the naked eye.

MEMSmerizing prospects

To Petersen, the disk drive and nuke projects are prime examples of how engineers "are looking at MEMS as a credible technology to fit into their systems." Other experts envision entirely new MEMS systems. DARPA is sponsoring a project at TRW Space and Electronics Group in Redondo Beach, California, to develop a MEMS-based system for steering miniature satellites, which might be "as big as your fist [and] might weigh as little as 1 kilogram," says TRW project scientist David Lewis. Swarms of such satellites could, for instance, be arrayed as huge radio telescopes.

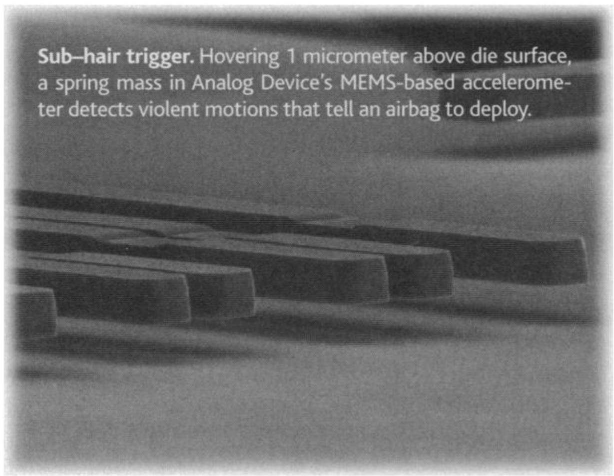
The MEMS system would serve for nudging each satellite into a precise spot, then holding it there, so that it works in sync with the others. To create this propulsion system, Lewis and colleagues patterned more than 100 microthrusters into a silicon wafer. Each thruster, which can be controlled individually, includes a cavity of a specific shape, a nozzle, and heaters that ignite dollops of propellant. "We have built these. We have fired them in the laboratory. They work," says Lewis.

But hurdles must be surmounted before a micromachine revolution catches up to—let alone eclipses—the microelectronics revolution. One key issue is to develop standards of performance, reliability, and failure as rigorous as those in the microelectronics industry. "With integrated circuits, there is so much infrastructure in place that you know what the pitfalls are," McWhorter says. "What are the equivalent failure mechanisms for MEMS? How do you model these? How do you develop algorithms that allow you to burn in and screen thousands of freshly minted MEMS? How can I ensure that I can put a micromechanical locking device in a weapon, that it can sit in a silo for 25 years, and the first time you want it to work, it will turn over and operate correctly?"

To Markus, known to her colleagues as the "Queen Mother of MEMS" for nurturing the field, these issues are growing pains that MEMS will soon leave behind. As a sign of the field's growth, Markus's MEMS program, which in the last several years has converted about 1000 blueprints into working MEMS, is going private next year.

Markus says MEMS have an appeal that is rare in today's high-tech: They hark back to last century's machine age, when you could see how something worked just by looking at it. "When you look at an integrated circuit under a microscope, you see a bunch of lines," she says. Nothing moves. With MEMS, however, you see motors driving shafts turning gears that turn other gears, push plungers, and so on. "When you design a MEM, you design it with parts that move," Markus says. "And when they are done, you watch them move and do things."

–IVAN AMATO



Sub–hair trigger. Hovering 1 micrometer above die surface, a spring mass in Analog Device's MEMS-based accelerometer detects violent motions that tell an airbag to deploy.

CREDIT: (BOTTOM) ANALOG DEVICES INC.

Ivan Amato is a correspondent for National Public Radio and the author of *Stuff*, a book about advances in materials science.