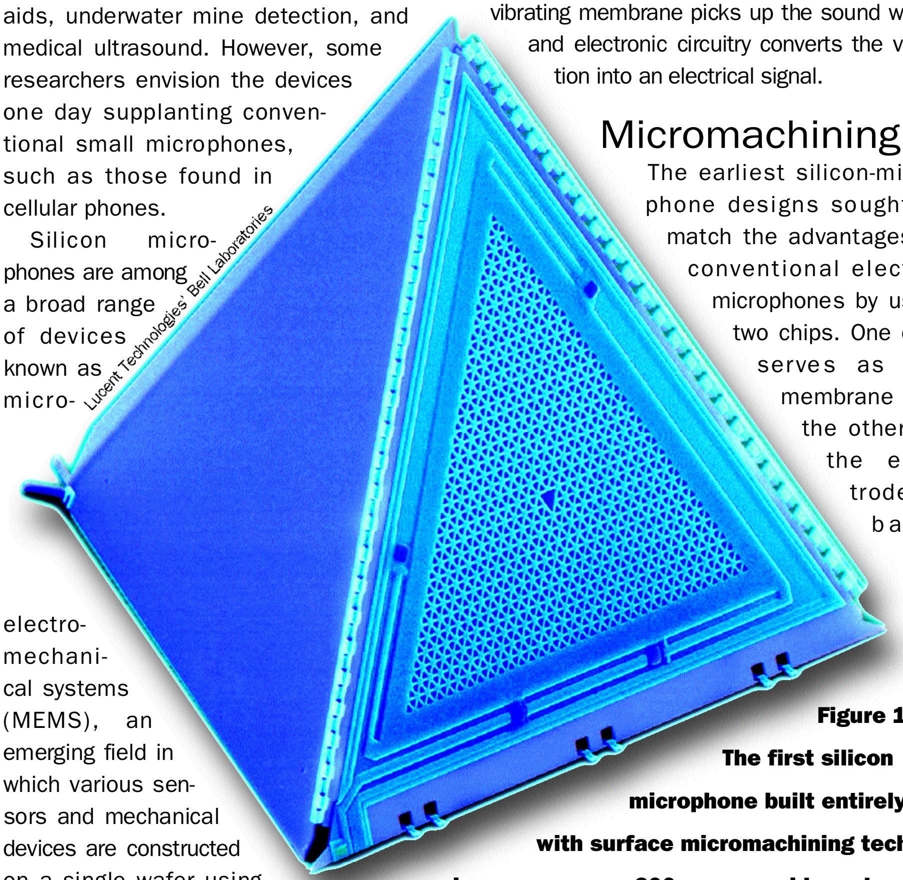
by Jennifer Ouellette

The Incredible Shrinking Microphone

Researchers and electronic companies are abuzz about a new generation of tiny microphones carved into silicon integrated circuits (ICs), often combined with electronic circuitry components. Generally referred to as silicon microphones, the devices are expected to find initial application in high-end markets such as hearing aids, underwater mine detection, and medical ultrasound. However, some researchers envision the devices one day supplanting conventional small microphones, such as those found in cellular phones.

Silicon microphones are among a broad range of devices known as microelectromechanical systems (MEMS), an emerging field in which various sensors and mechanical devices are constructed on a single wafer using processes developed for making ICs. According to Marc Fischer of Darmstadt University of Technology in Germany, the chief advantage of micromachining silicon microphones is cost. Several sensors can be processed on a chip simultaneously and can be integrated with passive and active electronic devices.

Micromachining makes it possible to precisely control layer thickness and lateral dimensions in the submicrometer range, yielding high precision and reproducibility. “By using silicon micromachining, one is able to design new types of sensors using the special mechanical and electrical properties of silicon,” Fischer says.



Lucent Technologies' Bell Laboratories

Figure 1. The first silicon microphone built entirely with surface micromachining techniques measures 300 µm on a side and was assembled by hand under a microscope.

Most handheld consumer products requiring microphones—such as cellular phones and portable tape recorders—use the electret-condenser microphone invented at Bell Laboratories in the 1960s. These microphones are preferred for their acoustical properties and low price, usually less than $1. In these devices, a vibrating membrane picks up the sound wave, and electronic circuitry converts the vibration into an electrical signal.

Micromachining

The earliest silicon-microphone designs sought to match the advantages of conventional electret microphones by using two chips. One chip serves as the membrane and the other as the electrode or backplate, which together form a capacitor. As the membrane vibrates in response to sound, the capacitance changes, creating an electrical signal in a circuit connected to the device. Two-chip capacitive silicon microphones have good acoustical properties, but new manufacturing techniques now enable the creation of the entire device on a single chip. Single-chip designs are favored because they do not require bonding two chips together. However, the production process is more complex and expensive than that for two-chip silicon microphones.

There are also piezoresistive and piezoelectric silicon microphones. The piezoresistive versions are one-chip devices that use materials as membranes whose electrical resistivity changes with the mechanical stress, caused by the deflection of sound waves. Piezoelectric microphones have a similar design and operation, but their materials generate electrical potential differences at the surface instead of changing resistivity. More radical designs include the two-chip optical microphone, which modulates light, and the field-effect transistor (FET) microphone, in which the vibration of the membrane produces a varying electric field that modulates the amount of current flowing through the FET.

Optical microphones are ideal for applications in which strong external electric or magnetic fields could cause interference, according to Gerhard Sessler, head of the electroacoustics research group at Darmstadt. Sessler, one of the pioneers of silicon-microphone technology, co-invented the electret-condenser microphone with James West while at Bell Labs.

Emkay Innovative Products established a partnership last year with the Institute of Microelectronics (IME) to develop and commercialize its microphone technology. The company is a subsidiary of Knowles Electronics, a leading manufacturer of transducers and receivers; IME is an independent nonprofit R&D laboratory in Singapore. Peter Loeppert, vice president of IC technology at Knowles, describes the device—which is 75% smaller than conventional microphones—as a “breakthrough technology [that] has yielded the world’s smallest microphone together with exceptionally high performance.”

At Lucent Technologies’ Bell Laboratories, a team led by Peter Gammel, head of wireless components research, has constructed a pyramid-shaped silicon microphone that measures 300 µm on a side and about 300 µm high. Lucent’s is the first silicon microphone whose parts were built entirely with surface micromachining techniques, in which thin films are deposited on a silicon surface and

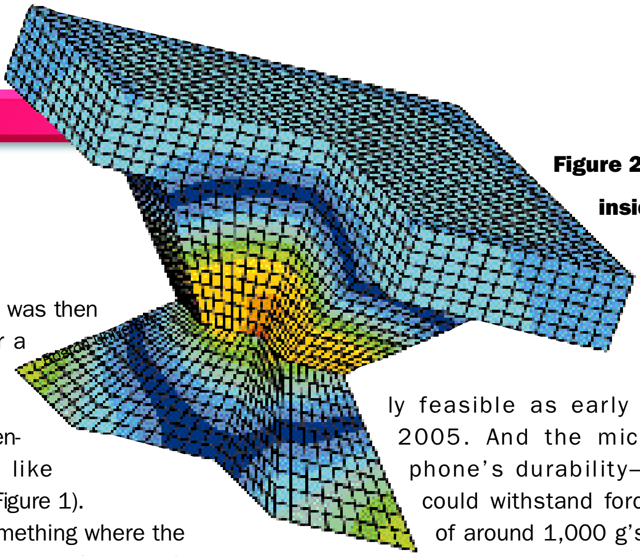


Figure 2. Computer simulation of the pressure field inside an optical silicon microphone.

then etched. The prototype was then assembled by hand under a microscope by folding several pieces on the surface to create a three-dimensional structure, much like micrometer-scale origami (Figure 1).

"We wanted to have something where the micromachined device is not merely a standalone component, but can be integrated with the silicon," says Gammel. "It then becomes part of the overall silicon integrated-circuit industry and can follow the same performance trends."

Once silicon microphones become as ubiquitous on chips as transistors, he adds, it will be possible to create large arrays for use in hands-free microphones in automobiles and in speaker phones for full-duplex conference calls. The arrays would not only detect the speaker's voice, but signal processing capabilities could cancel out extraneous noise and interference and make it possible to distinguish one speaker from another. The arrays would also make good candidates for advanced directional microphones.

Gammel emphasizes that Lucent's efforts in this area focus on developing systems to enhance the performance of ICs, rather than targeting specific applications. However, the microphone is a critical component for the eventual development of a Dick Tracy watch: the two-way, voice-activated video phone worn on the wrist that debuted in the popular comic strip in 1946.

The Bell Labs researchers have also built a tiny radio-frequency filter 100 times smaller than the conventional ceramic filters used in cellular phones, and a micrometer-scale inductor. Both devices can be incorporated with the microphone onto a single chip. Gammel speculates that all the components for the Dick Tracy watch should be technically feasible as early as 2005. And the microphone's durability—it could withstand forces of around 1,000 g's—would theoretically make it possible to implant it in a golf ball, tennis ball, or baseball. "Imagine watching a game on television and listening to what a baseball 'hears' when it is hit for a home run," says Gammel.

The Cutting Edge Meets the Classics

Any doubts as to the performance characteristics of the new silicon-microphone technology should be laid to rest when people listen to two of the first recordings made using the devices. Wolfgang Niehoff's group at Sennheiser Electronics recently produced a CD of classical recordings to showcase its miniature optical silicon-microphone technology. The studio-quality CD features performances of works by composers that include Brahms and the Johann Strausses, *père et fils*, including the "Radetzky March" and the "Tik-Tak Polka." The digital stereo recordings were performed by the Soloists of the Johann-Strauss Orchestra.

Peter Gammel's team at Lucent Technologies' Bell Laboratories has made a recording of a famous Puccini aria to demonstrate the capabilities of its prototype device.The recording was made directly from a CD—at a sound pressure level about the same as that of a live performance—using a set of reference speakers and a MEMS microphone hooked directly to a computer recorder. Both the microphone and the speaker were isolated to remove background reflections.

Gammel's team debated whether to go classical or record Jimi Hendrix's wailing-guitar instrumental rendition of "The Star-Spangled Banner." The aria—"Nessun Dorma" from *Turandot*, as performed by Luciano Pavarotti—finally won out. It is easier for the human ear to distinguish sound quality in a singing voice than in the heavy feedback and distortion that characterize Hendrix's musical style. But Gammel admits to an inside joke. As the recording switches from the original CD to that made with the MEMS microphone, the lyrics translate as "I will be victorious."

Several research groups based in Germany are developing commercially viable silicon microphones. Robert Bosch GmbH in Stuttgart has collaborated with Microtronic, a Danish firm, to create silicon wafers studded with condenser microphones. Only 2 mm^2 in area, the device's charged membrane (400 nm thick) is capable of converting sound vibrations into electrical signals as well as conventional microphones do.

Sennheiser Electronics (Wedemark, Germany), Europe's leading manufacturer of commercial microphones, has a two-pronged R&D effort. The first is a collaboration with the University of Twente in The Netherlands to develop a radical new silicon-microphone design that requires no outer membrane. Instead, it employs a transducer to sense the particle flow in an acoustic wave. Called a "microflown," the device was originally invented by Hans-Elias de Bree, then a Twente graduate student. He has since founded Microflown Technologies, which is participating in the Sennheiser– Twente collaboration. Microflown performance characteristics are now close to those of condenser microphones used in telephone receivers, and they have the added advantage of eliminating background noise.

The second effort, headed by Wolfgang Niehoff, is the development of an optical microphone in which sound is recorded by measuring changes in the intensity of a light beam inside the device. An advantage of this design is that the microphone head and photodetector can be placed several hundred meters apart, making it an ideal choice for use in strong magnetic fields or in difficult-to-reach places.

Sessler and his Darmstadt research group are experimenting with several designs, including optical and FET devices. Optical silicon microphones are particularly promising as a solution to the short-lifetime problems of small, humidity-sensitive microphones, such as those used in theaters.

Young Cho of the National Aeronautics and Space Administration has built an optical prototype in which red laser light passes through an optical fiber, bounces off a silicon nitride membrane, and travels back through the fiber.

Variations in light intensity generated by the membrane vibrations are converted into an electrical signal. According to Cho, the device is 1,000 times more sensitive than previous fiber-optical pressure sensors and commercial reference microphones.

Researchers at Boston University, led by Allan Pierce, are developing an underwater acoustic sensor system that uses an optical silicon microphone to detect mines in surf and near-shore waters (Figure 2). Currently, divers must search for these mines. However, visibility is limited to about 1 m because of the large quantity of silt and bubbles suspended in the water. "This means that the divers often find objects by swimming into them, which obviously has severe consequences if the object is a mine," says Robin Cleveland, a member of the BU research team. "Sound has the potential to 'see' farther through silty or bubbly water than does light."

The BU hydrophone features a small membrane carved into a solid piece of silicon, which vibrates when hit by sound waves. The vibrations are detected optically by bouncing a laser beam off the membrane. The BU team currently has a working prototype less than 1 mm thick. The next step is to arrange several such devices into an array. The ultimate goal is to incorporate more than 10,000 independent sensors into either a handheld system or goggles (creating an "artificial eye"), which would supply divers with a three-dimensional image in real time. The technology could also be applied in medical ultrasound.

Challenges ahead

Gammel cites manufacturing, reliability, and packaging problems as the primary challenges to commercializing silicon microphones. "Many people look at these small structures and they appear to be very fragile," he says. However, he argues that the MEMS-based sensors used for air-bag deployment offer evidence that this notion is largely a misperception. Packaging is a central issue in adapting silicon microphones to cellular phones. Unlike air-bag sensors, which are in a hermetically sealed package, cellular phones require the microphone to be coupled to the outside world—usually via a rubber structure—yet still protected from damage.

High costs related to the complex manufacturing process are another potential barrier to broad commercialization. Cost depends on the number of devices fabricated, according to Fischer, who estimates that silicon microphones processed in large batches would cost about $10 each if 100,000 devices a year were fabricated. Therefore, he expects initial applications to focus on high-end markets such as hearing aids.

Nevertheless, "for me, there is no doubt that there will be silicon microphones with good acoustical properties [commercially available] in the near future." Adds Sessler, "In a few years, as these devices are used in more and more applications, prices will come down and they will conquer some of the microphone market, now estimated to be close to 1 million units per year." Ω