

THE LITTLE MACHINES THAT ARE MAKING IT BIG

Imagine a world with machines the size of mites tending to all sorts of jobs. Some of them keep cars running smoothly and safely, saving hundreds of thousands of people from perishing in auto accidents. Other machines rout petabits (peta = 10^{15}) of information each second, play movies downloaded from the World Wide Web, or perform scientific measurements of an unprecedented sensitivity and precision. Chip-sized chemical factories produce dangerous materials, but only when and where needed.

Such a world exists today: We live in it. It is the world of modern silicon micromechanics.¹ This world was anticipated with remarkable foresight by Richard Feynman more than 40 years ago, when transistors were a new and unproven technology and integrated circuits (ICs) were still many years into the future. In his 1959 talk, "There's Plenty of Room at the Bottom," published shortly thereafter,² Feynman suggested what micromachines could be, why one would want to use them, how to build them, and how physics for machines at the microscale would be different than for machines at the macroscale (see box 1 on page 39). Nowadays, it is possible to fabricate inexpensive micromachines that range in size from 0.1 to 100 microns, require little power, and operate at high speed. Such qualities make micromachines a compelling choice for a wide variety of applications. Micromechanics technology is profoundly changing the way we think about and use machines.

True machines

The microscopic devices we are talking about are machines in the truest sense of the word. They have moving parts, sometimes millions of them. They can be as simple as cantilevers or as complicated as mechanical clocks. Elements such as rotary joints, springs, hinged plates, simple screws, suspended and unsuspended beams,

Microelectromechanical systems are currently used in a variety of applications, including triggering airbags and measuring the Casimir force. In the future, they may revolutionize the way we think about machines.

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diaphragms, mechanical striplines, and latches can be built and used reliably in a wealth of applications.

Micromachines, or microelectromechanical systems (MEMS), are made using a variety of techniques (see box 2 on page 40) originally developed for use in the \$200-billion-per-year semiconductor industry. Sophisticated deposition tools, lithographic

processes, wire bonders, photoresists, packages, Si wafers, modeling tools, and even reliability methodologies can be used in making MEMS devices. The benefit of being able to recycle existing technologies cannot be overestimated; recycling can be especially useful for those who design devices intended primarily for scientific applications, typically with almost no development funds.

The worldwide market for MEMS is estimated to exceed tens of billions of dollars in the next several years. In this article, we will focus on a number of key application areas: automobiles, handheld phones, display technologies, lightwave systems, and scientific measurements.

Car talk

An important, commercially successful MEMS device in widespread use today is the automotive airbag sensor,³ which measures rapid deceleration of a car and triggers the explosive filling of an airbag. Before the use of a MEMS device in this application, airbags were typically triggered by an electromechanical device roughly the size of a can of soda, weighing several pounds and costing about \$15. Now the same function is accomplished with a MEMS device that costs just a few dollars and is the size of a small cube of sugar (see figure 1). The smaller size of the MEMS device allows it to respond more quickly to rapid deceleration. As a consequence, it is now practical to have airbags in car doors to protect occupants against side impacts. MEMS airbag sensors have an additional important advantage over their macromechanical predecessors—integrated electronics that allow for self-testing. The test is initiated whenever a driver turns on the ignition, and its successful conclusion is indicated by an illuminated dashboard light.

Other applications for MEMS in automobiles include inertial sensors for keeping track of a car's location, tilt

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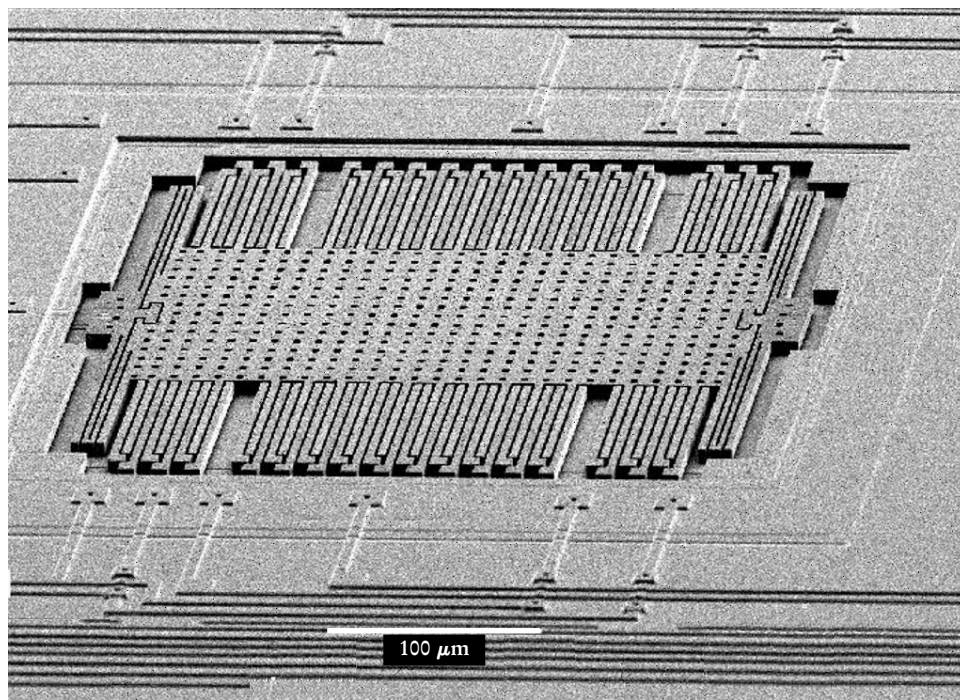


FIGURE 1. A MEMS accelerometer is a key component of many automobile airbag sensors. The device consists of a center region, the proof mass, which is connected by springs to the surrounding structure. The interdigitated fingers are capacitors used by on-chip electronics (not shown) to sense acceleration. (Courtesy of John Yasaitis, Analog Devices Inc.)

meters to warn of impending roll-overs, and pressure gauges used in the engine to assure proper and efficient operation. In the near future, MEMS devices will be key components of smart tires, which will remain properly inflated at all times. If tires are maintained with proper

part of a feedback loop that includes a pump in the car. Thus, the responsibility of maintaining proper tire pressure rests with the car, not with the driver.

Automotive applications mark the beginning of a radically new technology. The airbag sensor in particular, with

air pressure, not only will cars be safer, but, in addition, the US could reduce fuel consumption by an estimated 10%. Smart tires have microscopic pressure sensors as

Box 1. How Is Micromechanics Different?

One of the charms of working in the microworld is that mechanics can be quite different at the microscopic scale from what we experience at the macroscopic scale of daily life: One has to develop a whole new intuition about mechanical things. In the microworld some things are the same as in our world, some are quite different, and the fun is figuring it all out.

The main difference in the microworld is that the surface area to volume ratio is very different from that for mechanical devices in the macroworld, so the relative importance of inertia and friction are different, and surface effects can be important.

We who live at a macroscopic scale notice the effects of inertia every day. Balls keep rolling after being pushed. Birds glide. Swimmers coast to the edge of a swimming pool. Friction is important but not dominant. However, at the microscale, the relative importance of friction and inertia switch. Friction dominates. Even if it were as smart as Newton, a paramecium would never be able to discover inertia—it stops dead in its tracks the instant it stops swimming.

For micromachines, surface effects are paramount. For example, one can build devices that change their overall mechanical response due to a phase transition in a single monolayer on the surface.

Another interesting effect becomes prominent at the microscale, something called stiction, a composite of “sticky” and “friction.” At the microscale, molecular attractions can overwhelm restoring forces for simple objects. When tiny objects touch, for example, they can get stuck forever. One has to worry about whether a simple cantilever (a beam supported at one end, like a diving board) will ever come back up after its end touches down.

Two types of stiction are worrisome. The first is release stiction. This type arises because the final step in the fabrication of micromachines, called the release step, often uses wet chem-

istry. If one is not careful, surface tension can pull things together as the liquid dries. (Think of two wet pieces of paper.) A standard solution to this difficulty is to use supercritical drying, which, by going around the critical point, avoids going across a liquid-vapor phase line and having a meniscus to worry about.

The other type of stiction is in-use stiction, where elements of a micromachine get stuck together if they are allowed to touch. Techniques to defeat in-use stiction range from using dimples and fingers to minimize contact area, to applying very elaborate nonstick coatings. At the microscopic scale, water is an effective glue that will gum up the operation of a micromachine. Commercial devices use hermetic, waterproof packages to resolve this problem.

Another interesting difference between macroscopic and microscopic devices is the nature of the forces that move things around. At macroscopic scales, electromagnetic forces tend to be used to build strong motors. Magnets and coils of wire with currents in them can produce large forces. In the macroworld, electrostatic forces are mainly useful for amusements like sticking balloons to a wall. At the microscale, things are different. For a fixed current density in a wire, electromagnetic forces get smaller when the sizes of wires and magnets scale down, while electrostatic forces can become large enough to be practical as objects get closer together. Therefore, electrostatic actuation is a standard technique for micromachines while it’s seldom used for macromachines.

Other interesting effects that are safely ignored at macroscopic scales can become important in the microworld, including quantized thermal conductance, Brownian motion, mesoscopic mechanical properties, and exotic dislocation line motions. Life is very interesting in the microworld and we are just beginning to find out how different it is.

Box 2. How Are MEMS Devices Built?

Microelectromechanical systems (MEMS) research is an outgrowth of the vast capabilities developed by the semiconductor industry. Processes originally developed for building microelectronic devices are also useful for building MEMS devices that are capable of motion on a microscopic scale.

MEMS devices are built using two broad classes of techniques. In the first, surface micromachining, a device is constructed in much the same way as a silicon integrated circuit (IC). As illustrated in the top figure, various films such as polysilicon (whose first layer is called Poly 0), silicon nitride, silicon dioxide, and metals are deposited and patterned to produce a complicated, multilayered, three-dimensional structure. Then a selective etch removes some of the layer materials, leaving a device with movable elements (bottom figure). This last process, called a release step, is the major difference between IC and MEMS device fabrication.

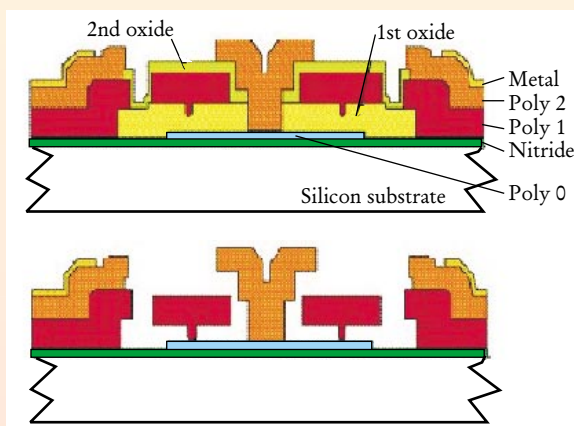
The other class consists of the so-called bulk micro-machining techniques. In these, bulk wafers of Si are etched using either anisotropic wet etching with, for example, potassium hydroxide, or plasma techniques such as deep reactive ion etching. DRIE is particularly noteworthy because it allows one to etch cavities with nearly vertical walls completely through a Si wafer.

A process that combines elements of both classes of techniques is LIGA (an acronym for the German words for lithography, electroplating, and molding) which uses a thick photoresist, typically exposed with a synchrotron source, followed by the electrodeposition of a thick metal such as nickel. This technique spans the range from micro to macro, allowing for the fabrication of devices with dimensions ranging from microns to millimeters.

MEMS devices are made using IC batch-processing. Thus, even though fabrication may consist of complicated, multistep processes, the devices are economical to produce, because many

are made simultaneously. In addition, designers and manufacturers can profitably use previous-generation equipment of the IC fabrication industry. Nowadays, an IC factory costs more than \$1 billion and is obsolete in less than five years. So the ability to reuse its equipment for a new class of cutting-edge products is very appealing. IC fabrication techniques also allow designers to integrate micromechanical, analog, and digital microelectronic devices on the same chip, producing multifunctional integrated systems.

Finally, MEMS devices have proven to be robust and long-lived, especially those devices whose parts flex without microscopic wear points. Research into the effects of shock, vibration, number of cycles of operation, thermal history, aging, and so forth has been extremely active over the past decade, with the result that micromechanics can now produce microscopic versions of most macromachines.



its better than 100 million device years of experience in the inhospitable environment of a car, has proved the reliability of this technology. The experience gained in the automotive arena can be used to guide the application of MEMS devices in other equally demanding environments.

Micro-microphones

Modern handheld phones need to be small and inexpensive, and should not draw a lot of power. At the same time, they must be functional. These requirements are tailor-made for micromachines. MEMS devices are low power because they are typically electrostatically operated. They are small and can be easily integrated with both radio frequency analog circuits as well as digital circuits. Thus, one can build on-chip devices to replace large, off-chip components that require expensive interconnections to the rest of the circuit. Candidate devices for use in handheld phones include inductors, varactors (voltage-tunable capacitors), filters, tank circuits, RF switches, and micro-microphones.⁴

The micro-microphone shown in figure 2 is an interesting example of such an on-chip device. In a typical cellular telephone, the microphone is large. At first, it seems a good candidate for miniaturization and integration with the Si electronics. But the disparity in size between the wavelength of sound and the size of MEMS devices suggests that MEMS micro-microphones would not work. The way around the difficulty is to use very sensitive readout electronics to compensate for the poor acoustic coupling.

On-chip microphones might make it possible to build

radios on a chip. Or, it may be possible to use arrays of micro-microphones for acoustical source location to minimize coupling to extraneous noise sources—much as humans do with their two ears when having a conversation in a noisy room. MEMS devices are allowing acoustical engineers to accomplish tasks that were previously thought to require large and expensive equipment.

Cinéma vérité

An early MEMS device used for a variety of display applications is the Texas Instruments Digital Micromirror Device (DMD)TM. As shown in figure 3a, the DMD consists of an array of small ($16 \times 16 \mu\text{m}$) mirrors each able to rotate by ± 10 degrees.⁵ DMD arrays can contain more than a million mirrors. When integrated with standard semiconductor devices, these arrays can be a key component of highly functional, high-performance systems. For example, DMDs illuminated with intense light sources can make displays for personal computer projectors, video walls, high-definition TVs, and digital cinemas, to name just a few. Because the mirrors reflect light of a very high intensity, DMDs can be used in large-venue systems, such as digital cinemas, for which competitive liquid crystal technologies are ill suited.

Figure 3b shows the detailed construction of the mirrors. As in the case of ICs, microlithography allows one to replicate many identical mirrors after a basic mirror cell has been developed.

The DMD has enjoyed significant commercial success despite the considerable challenges of bringing this very

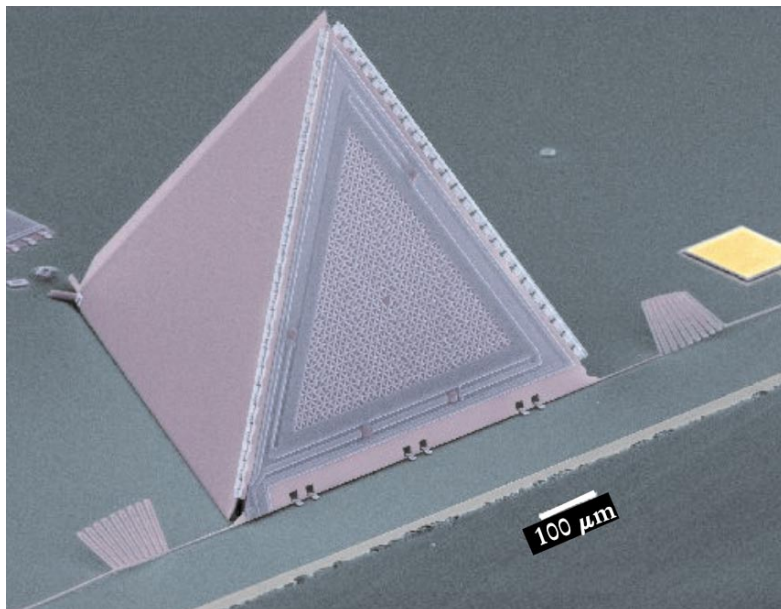


FIGURE 2. A MEMS MICROPHONE is made by patterning plates in a plane and then folding them up by hand. The hinges on the edges are visible. Behind the open grill on the front is a membrane; it and the grill together form a capacitor. Sound moves the membrane relative to the grill and electronics (not shown) detect the changes in capacitance. (Courtesy of Flavio Pardo, Bell Labs, Lucent Technologies.)

complex device to market. Initially there were difficulties with the reliability of the DMD and with packaging the device to keep water and dust out. Fortunately, these problems have been solved and, to date, more than 500 000 systems have been shipped.

Switching the light fantastic

Not too long ago, many of us pointed to the telephone as a communications tool essential to our social and work lives. Now many of us cannot imagine living and working without the Internet. Photonics is the technology that makes the Internet possible: Almost every bit sent over the Internet is transmitted as light on optical fibers.

A typical lightwave system consists of optical fibers routed between major metropolitan areas. Data are usually sent over many different wavelengths of light on a single fiber because light is uncharged and the different colors are largely

noninteracting in clean glass. The combining of several wavelengths of light on a single optical fiber is called WDM, or wavelength division multiplexing. More than a thousand separate wavelengths, or channels, can be sent transmitted on a single fiber.

The data capacity of fibers has been doubling every six to nine months. Impressive improvements in the transparency of glass optical fibers have allowed scientists and engineers to increase the data carrying rate of a single fiber to the previously unimaginable levels of more than 10^{13} bits per second. But the capacity to carry a great deal of data is not enough. Data need to be manipulated by, for example, being routed from one fiber to another. MEMS devices are part of the technology that will carry out such manipulations, allowing us to benefit from continuing increases in fibers' data capacity.

The sizes of MEMS devices make them well suited to optical applications. The wavelength of visible light is an appreciable fraction of a micron, comparable to the size of the smallest micromachines; a semiconductor laser has a length scale measured in tens of microns; and an optical fiber has a diameter of roughly $100\mu\text{m}$, comparable to large MEMS devices.

Simple MEMS devices include switches that take a single optical input and divert it to either of two outputs, and optical shutters, which simply block light from going downstream. More complex micromachines can adjust the spectral response of an optical amplifier much like the slide switches on a stereo adjust the

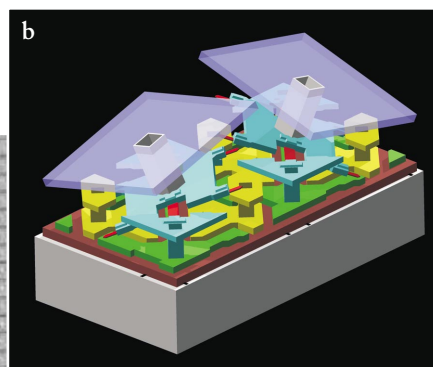
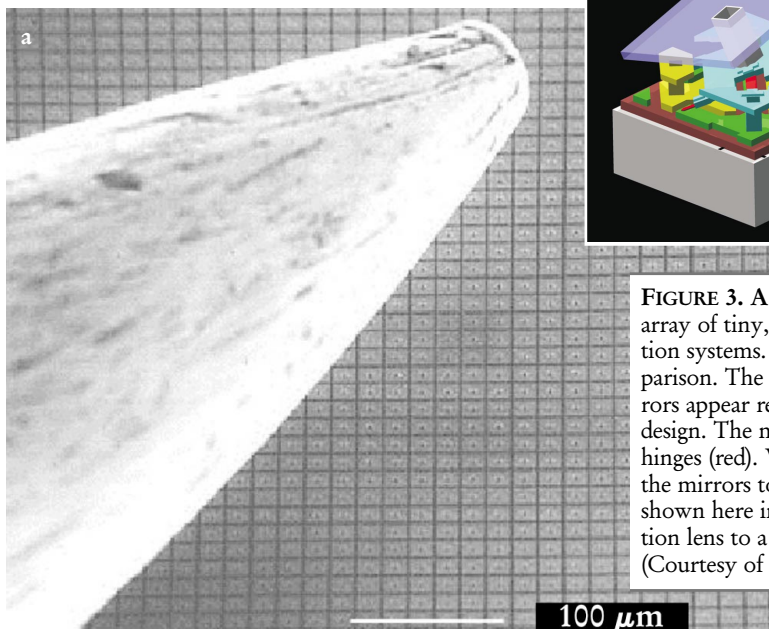


FIGURE 3. A DIGITAL MICROMIRROR DEVICE (DMD)TM is an array of tiny, tiltable mirrors that can be used in a variety of projection systems. (a) A DMD and the point of a needle for a size comparison. The array has been imaged at an angle, so the square mirrors appear rectangular. (b) Two mirrors showing the details of their design. The mirrors (blue) and the support posts (gray) rotate about hinges (red). Voltages applied to the address electrodes (yellow) force the mirrors to rotate to either the on or off position; one mirror is shown here in each state. On-mirrors reflect light through a projection lens to a screen, whereas off-mirrors reflect light to an absorber. (Courtesy of Larry Hornbeck, Texas Instruments.)

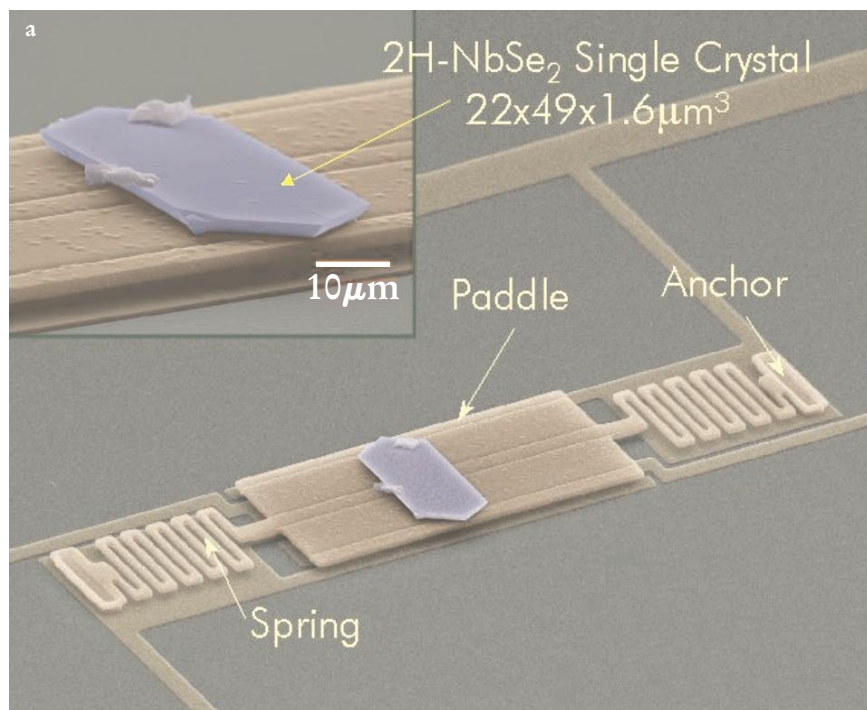


FIGURE 4. A MEMS MAGNETOMETER can measure single vortex flux jumps in a type-II superconductor. **(a)** A small sample, which is several tens of microns on a side, is glued to a paddle that rotates about its center axis. The paddle and attached springs make up a torsional oscillator with a resonant frequency typically around 40 000 Hz and a quality factor typically around 250 000. The oscillator is the frequency-determining element in a feedback loop that is similar to a quartz crystal resonator. As flux lines enter the sample, they cause small changes in the restoring torque of the resonator and the frequency of the loop changes. An external frequency counter detects this change. **(b)** Frequency of the torsional oscillator plotted against the magnitude of a magnetic field applied parallel to the long axis of the sample (1 oersted = 79.58 ampere/meter). Single vortex flux jumps are clearly visible at fields above the lower critical field H_{c1} . (Adapted from ref. 10. Courtesy of Cristian Bolle, Bell Labs, Lucent Technologies.)

acoustical frequency response to mix in more treble or bass. Even more complicated systems include add/drop multiplexers, which can route individual optical wavelengths in a fiber to desired destinations.

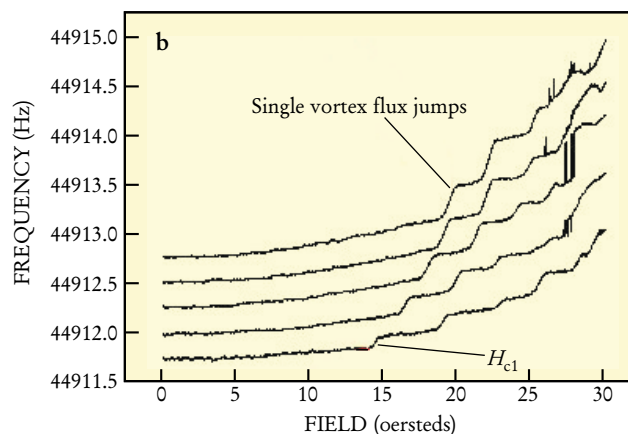
The applications for MEMS devices in lightwave systems^{6,7} range from variable optical attenuators, the optical equivalent of an electrical rheostat for adjusting the intensity of optical signals, to the application that launched a hundred startups—the complex optical cross-connect, also called an optical switch.

An optical switch routes data from one set of optical fibers to another at locations called nodes. With trillions of bits of data per second on a single fiber and hundreds to thousands of fibers entering and leaving a large node, the aggregate switching capacity needed can be enormous.

The standard way of switching the data was to convert the optical signals into electrical ones, use a large, fast electronic switch to route them, and then turn the signals back into light for transmission. Unfortunately, an electronic bottleneck has developed. The ability of fibers to transmit optical data has outstripped the ability of electronic devices to convert that data into electrical signals and switch it. The solution is all-optical switching—keeping the data as photons for both switching and transmission. Enter MEMS.

The basic idea with MEMS switches is to use microscopic mirrors to direct beams of light from many inputs to many outputs without slowing down the data streams by conversions from optical to electrical and back. Rerouting light with MEMS switches not only breaks the electronic bottleneck, it has many other advantages as well. It is data rate independent in the sense that a mirror's behavior is independent of how fast the light turns on and off. Likewise, a mirror's behavior is wavelength independent. MEMS switches are small and fast, use little power, and, above all else, are inexpensive.

When the optical switch is operating, light from an array of optical fibers is focused by an array of lenses so that the output of each fiber lands on its own mirror. Each



mirror can tilt along two directions and steer the beam to any single output fiber located in another array of fibers. Switches, roughly the size of soccer balls, with more than 1000 input and 1000 output ports have already been built with a demonstrated aggregate capacity of more than two petabits/sec. To put that into perspective, if everyone on the planet were to simultaneously make a telephone call or to browse the Web, the total rate at which information is transferred would be roughly one petabit/sec. This gives some idea of the power and potential of the MEMS technology.

The market for optical switches is estimated to become more than \$5 billion annually by the year 2005. That's why a large number of startups and established companies are working to develop these devices: There is a large pot of gold at the end of this particular rainbow.

Scientific measurements

We believe that MEMS devices are likely to play an increasingly important role in making scientific measurements. When one of us (DJB) was a student at Cornell University more than a few years ago, experimentalists

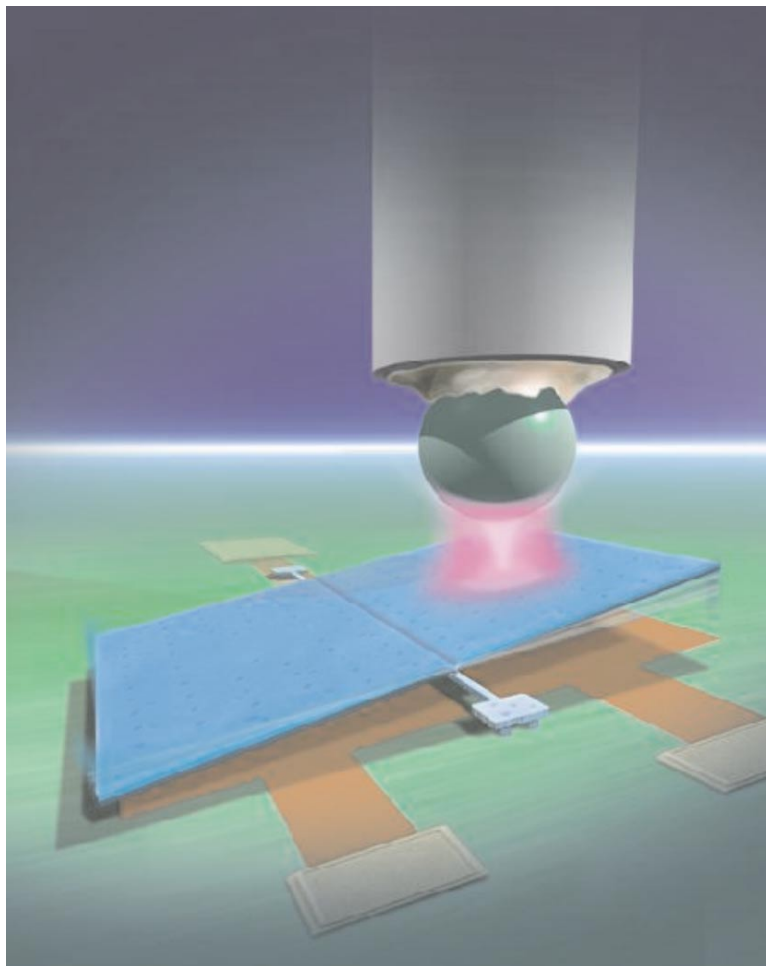


FIGURE 5. A MICROSCOPIC SEESAW allows one to measure the Casimir force. Under each of the two ends of the seesaw is a capacitor plate. When a metallized sphere is brought close to one end, the seesaw rotates slightly. As a consequence, the relative capacitance at each end of the seesaw changes, and can readily be measured with a bridge circuit. (Courtesy of Ho Bun Chan, Bell Labs, Lucent Technologies.)

were all sent off to the student shop to learn how to drill and turn and mill and tap metals so that they could build macroexperimental equipment. Students can now use computers and computer-aided design tools to help build micromachines used in their labs' scientific experiments. The files that they write on a personal computer get sent out to a "fab," where the devices they have designed are made and then shipped to the lab. Some have coined the phrase "the new physics machine shop" to describe the fabrication of micromachines for experiments in basic science. For the students taking this new approach, an ion mill is a more important tool than the metal mill many of us were taught to use when we were students. Both mills do the same job, but on very different length scales.

The art of scientific measurement is to achieve high accuracy and precision in the face of limited funds. MEMS devices are beginning to find numerous applications in this area. Examples include high-sensitivity magnetometers, micromachines that measure the Casimir force, calorimeters, bolometers, adaptive optics for astronomy and vision science,⁸ and devices for studying mesoscopic vortex physics. Here we consider high-sensitivity magnetometers and the measurement of the Casimir force.

High-sensitivity magnetometers

One of the most important properties of a solid-state material is its magnetization. MEMS devices provide a powerful new probe of this property, and are especially useful in the extreme limit of very high magnetic fields.

In recent years, experimental condensed matter physicists have developed a way to generate magnetic

fields with a strength of about 75 tesla. These fields, however, only last for a few milliseconds. MEMS magnetometers, using a microscopic Faraday balance, are able to measure the magnetization of a material in this brief period.⁹ The balance looks like a small trampoline. It is part of a capacitor, connected to a sensitive bridge circuit that allows small changes in the trampoline's displacement to be measured. A sample weighing roughly 1 microgram is glued to the balance and is placed in a pulsed magnet in a region where the field is reasonably high and the field gradient is nonvanishing. The sample is subject to a force proportional to the field gradient times the magnetization of the sample. By knowing the trampoline's spring constant, one can relate the displacement of the trampoline to changes in the magnetization as the sample responds to the rapidly varying magnetic field.

Another type of magnetometer, shown in figure 4a, is designed to probe the regime of single magnetic vortices entering and leaving a type-II superconductor.¹⁰ A small sample—several tens of microns on a side—is glued to a microscopic torsional oscillator whose oscillation frequency can be measured to high precision. The device is zero-field cooled to below the superconducting transition of the sample and a magnetic field, applied parallel to the long axis of the sample, is ramped up from zero. At H_{c1} , the lower critical field, vortices begin to enter the sample. As each vortex does so, it is pinned to the sample. Because the vortices are pinned to the sample, whereas the external field is constant, the magnetic torque $\mathbf{M} \times \mathbf{H}$ changes as the torsional oscillator rotates. In the small angle limit, the magnetic torque has the same form as the restoring torque of the oscillator. Thus, as vortices enter the sample there are, in essence, changes in the oscillator's torsion constant. These changes are manifested as small jumps in the oscillator's resonant frequency and are clearly visible in figure 4b. One can count individual vortices and probe the mesoscopic vortex regime, the magnetic analog of what is studied in electronic quantum-dot physics. The analogy is complete with the observation of vortex telegraph noise and the turning on of many-body effects as the number of vortices in the sample increases beyond several tens.

Casimir force measurements

The Casimir force exists between two uncharged metal surfaces due to zero-point fluctuations of the electromagnetic vacuum. It is a purely quantum-mechanical effect, predicted by Hendrick Casimir in 1948. Unlike the

Coulomb interaction, which varies inverse quadratically with distance, the Casimir force varies inversely as the fourth power (for planar conducting surfaces; in general, the force depends on geometry). Plates separated by 10 nm are subject to a Casimir pressure of about one atmosphere, but the Casimir force falls off so rapidly with distance that the gravitational and Casimir forces are roughly comparable for plates separated by as little as a micron.

Figure 5 shows a schematic of a microscopic seesaw device that has been used to measure the Casimir force.¹¹ As described in the figure caption, when a conducting surface is brought very near to one end of the seesaw, that end rises. By measuring the displacement, one can determine the Casimir force.

The Casimir effect has been exploited in the building of hysteric oscillators. In the future, the effect will enable construction of a new generation of exquisitely sensitive position sensors. In a very real sense, MEMS devices allow one to use a force created out of the vacuum.

A lesson from an old radio

In this article we have given the reader a mere glimpse of what has been done with MEMS devices and what may be accomplished in the near future. It is clear to us that the field of micromechanics will change the paradigm of what machines are, how and where we use them, what they cost, and how we design them. It may not be an exaggeration to say that we are on the verge of a new industrial revolution driven by a new and completely different class of machines.

The invention of the transistor may prove a useful guide for what to expect. When first discovered, the transistor was used as a replacement for vacuum tubes in applications, like radios, where vacuum tubes worked well enough. One of us (DJB) recalls that, in 1960, he received as a birthday gift a transistor radio whose case proudly announced that the radio had six transistors. Six-transistor radios would have been easy to predict in 1947 when the transistor was invented. Today, however, we take for granted microprocessors with tens of millions of transistors. No one in 1947 could have predicted such a thing and what it would do to our world.

We currently use micromachines to do things that in most cases can be done by macromachines. (The micromachines, however, do a better job.) In 20 or 30 years, though, society will be using micromachines in ways impossible for us to imagine today. Those of us working in the field of micromechanics look forward to helping make it happen.

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