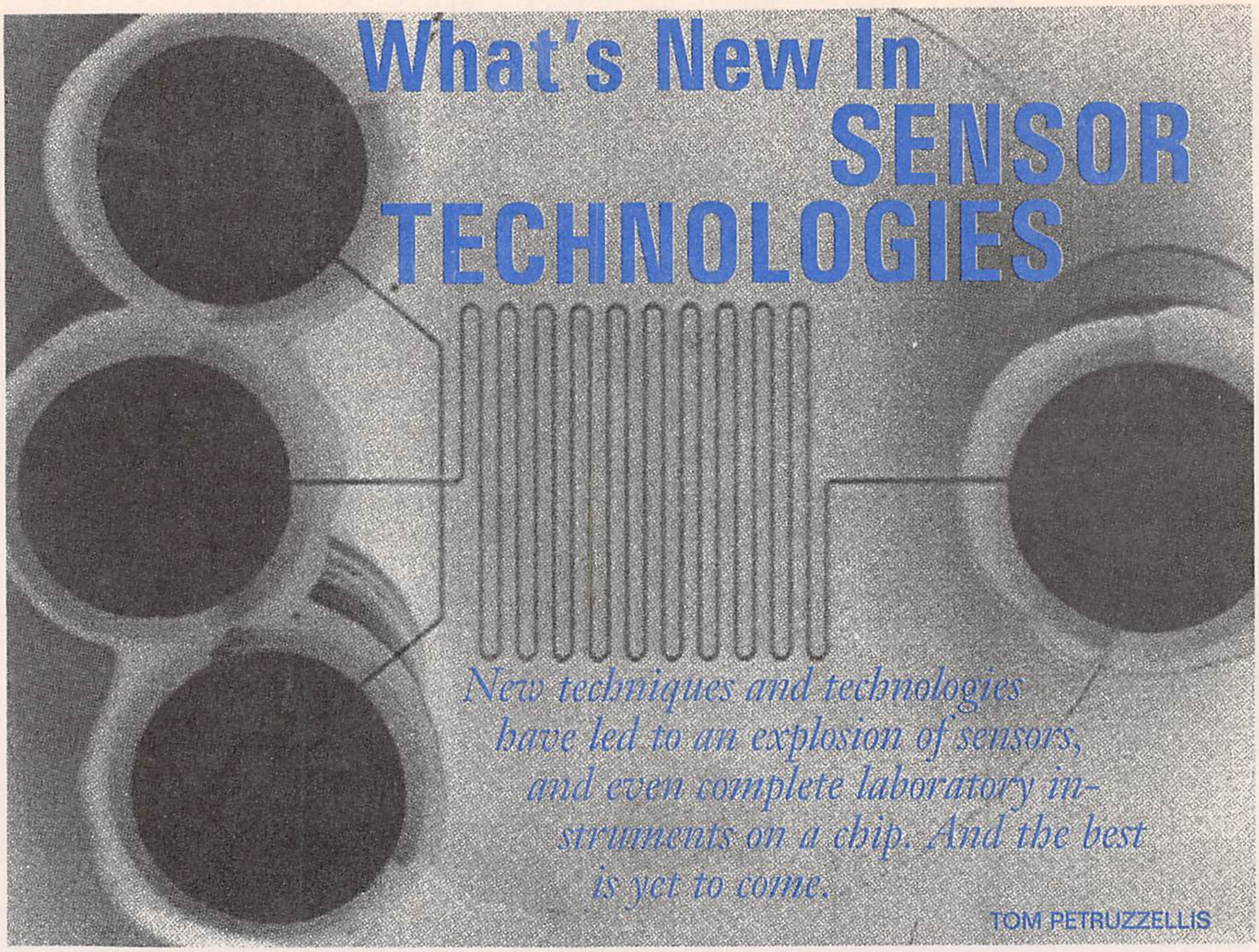
What's New In SENSOR TECHNOLOGIES



New techniques and technologies have led to an explosion of sensors, and even complete laboratory instruments on a chip. And the best is yet to come.

TOM PETRUZZELLIS

Most people might not have noticed, but a quiet revolution is taking place all around us. That revolution is in the area of sensor technology, and the result is a whole new brigade of advanced, highly-integrated smart sensors. And while that revolution might be "quiet," progress in this area is nothing short of astounding, with sensor technologies developing at such a rapid rate that new advances are taking place almost daily.

Sensors, Technology, and Us. The latest and most dramatic advances have been focused around the new micromachined thin-film sensors. Those include light sensors, pressure sensors, accelerometers, tilt sensors, resistance temperature detectors (RTDs), anemometers, and a host of gas and chemical sensor arrays.

Just how will these developments affect our professional and personal lives? Well, industrial process and control systems are already benefiting from smart-sensor technology. Advanced micro sensors have also moved into the medical field, producing many new diagnostic sensors ranging from silicon microprobes that can interface with a patient's nervous system to portable blood-chemistry analysis systems. The technology is making it possible to place complete systems on a single chip, and to place complete chemical laboratories in the palm of your hand.

Automobiles will also benefit from the new smart-sensor onslaught. Presently, there are about 20 sensors used in the average new car, and the number is growing. Many of the new micromachined automotive sensors will provide additional convenience and safety features based on new smart-sensor technology. Those could include failed-brake sensors, wheel-speed sensors, tire-pressure sensors, rate gyros for anti-skid braking, oil-degradation sensors, and new emission sensors.

The above just scratches the surface of what is now or soon will be possible. Let's look at some of the details.

Micromachining. Much of this new sensor revolution is based on the advantages of micromachining and thin-film-deposition techniques found in the semiconductor industry. Until recently, much of the work has centered on the bulk micromachining process. That technology involves using chemicals to machine pits or holes and structures into bulk silicon at the wafer level. Bulk micromachining has been well suited for pressure sensors and accelerometers.

However, a newer, and very promising technology used in advanced sensor manufacturing is the surface-micromachining process. Surface micromachining involves depositing layers onto a substrate of silicon and selectivity etching those deposited layers to form structures. Surface micromachining

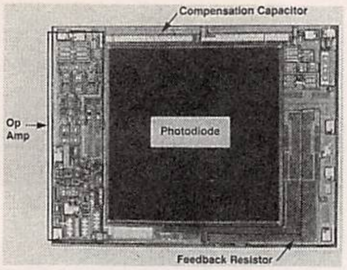


Fig. 1. The new Burr-Brown OPT 202/211 series optical detectors incorporate a large surface photodiode, an op-amp with an internal feedback resistor, and a compensation capacitor.

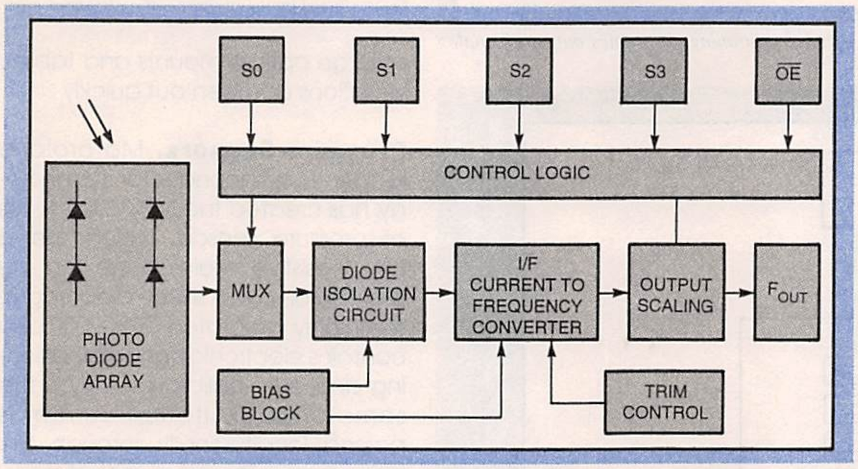


Fig. 2. The TSL-230, from Texas Instruments, can convert light intensity to a digital-compatible pulse train, providing a simple, low-cost means of getting light-intensity information into a digital system. A block diagram of that device is shown here.

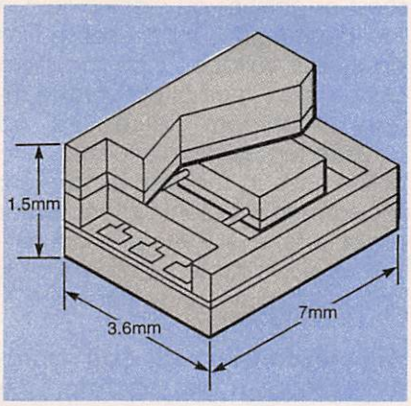


Fig. 3. In this capacitive acceleration sensor, the center layer forms a seismic mass that is suspended by two cantilever beams and located symmetrically between two plates, which act as electrodes. As the mass moves under acceleration, it changes the position between the plates and therefore causes a change in capacitance.

creates smaller, more intricate, and more precisely patterned structures since it takes advantage of photolithography used in making small ICs. Using that technology, it is possible to form tiny beams, masses, and other small structures with features as small as 1-2 micrometers.

Surface micromachining takes far less silicon real estate than the bulk micromachining process; the geometries are smaller because the etching tolerances are much tighter, and you only have etch one side of the wafer as opposed to two sides in the bulk-micromachining process. The surface-micromachining process can reduce the size on the order of $^1/_{10}$ and reduce the surface area on the order of $^1/_{100}$ as compared to bulk machining. Another great advantage to surface micromachining is that the electronic signal conditioning and the sensor can be combined on the same die or substrate; that is an important factor in keeping signal integrity and reducing noise. Surface micromachining promises to reduce costs, size, and heat generation and increase endurance and reliability.

Several major manufacturers, including Motorola, have been actively developing surface micromachined sensors. One area in which they have already gained a market presence is in consumer motion detectors. With the advantages it offers, and as other high-volume applications become practical, it is likely that surface micromachining will largely replace the bulk-machining process.

Optical Sensors. A number of new integrated thin-film sensors and arrays have already hit the marketplace. The new Burr-Brown OPT 202/211 series optical detectors incorporate a large surface photodiode, an op-amp with an internal feedback resistor, and a compensation capacitor all built into an 8-pin mini-dip package (see Fig. 1). The IC converts the photodiode's current output into a voltage while preserving a high accuracy since the detector is placed in close proximity to the op-amp electronics. Generally, the size of a photodiode and the speed of an amplifier determine the speed of an optical system. With a large photodiode and an integrated amplifier close by, good speed and accuracy are possible. Optical filters can be placed ahead of the detector to create any desired passband. Among other things, the OPT 202 can be used to create a low-cost integrated photometer that can operate from a single 9-volt battery.

A new high-accuracy, wide-dynamic-range light-to-frequency converter chip from Texas Instruments, the TSL-230, can convert light intensity to a digital-compatible pulse train, providing a simple, low-cost means of getting light-intensity information into a digital system. The highly integrated chip, a block diagram of which is shown in Fig. 2, consists of a 100-unit, multiplexed, photodiode array. The current output of the array is passed to a diode-isolation circuit that buffers the output and keeps the photodiode array's bias near zero. Next, the signal is passed to a current-to-frequency converter. The TSL-230 eliminates the need for an A/D converter, since the direct conversion to frequency is done right on the chip. The TSL-230 has two sets of digitally-programmable inputs to control sensitivity and scaling of the output. The 8-pin, 5-volt mini-dip is directly compatible with any microcontroller or computer. The applications for the light to frequency converter are enormous and include such things as water-turbulence sensing, chemical analysis, and process control. Chemical diagnostic applications range from smoke and gas detection to body-chemistry analysis. The new TSL-230 has already been put in widespread use by General Electric to measure water clarity in its new Profile series dishwashers.

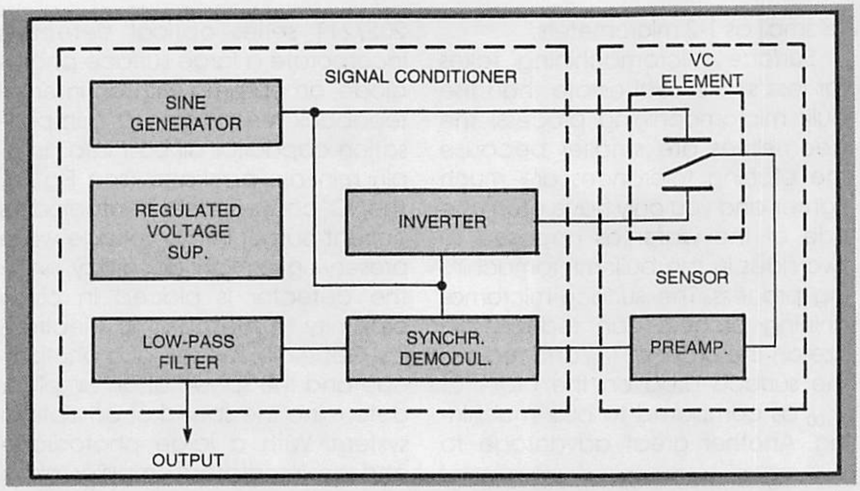


Fig. 4. The capacitive accelerometer's integrated signal-conditioning electronics output an analog signal that is proportional to the acceleration.

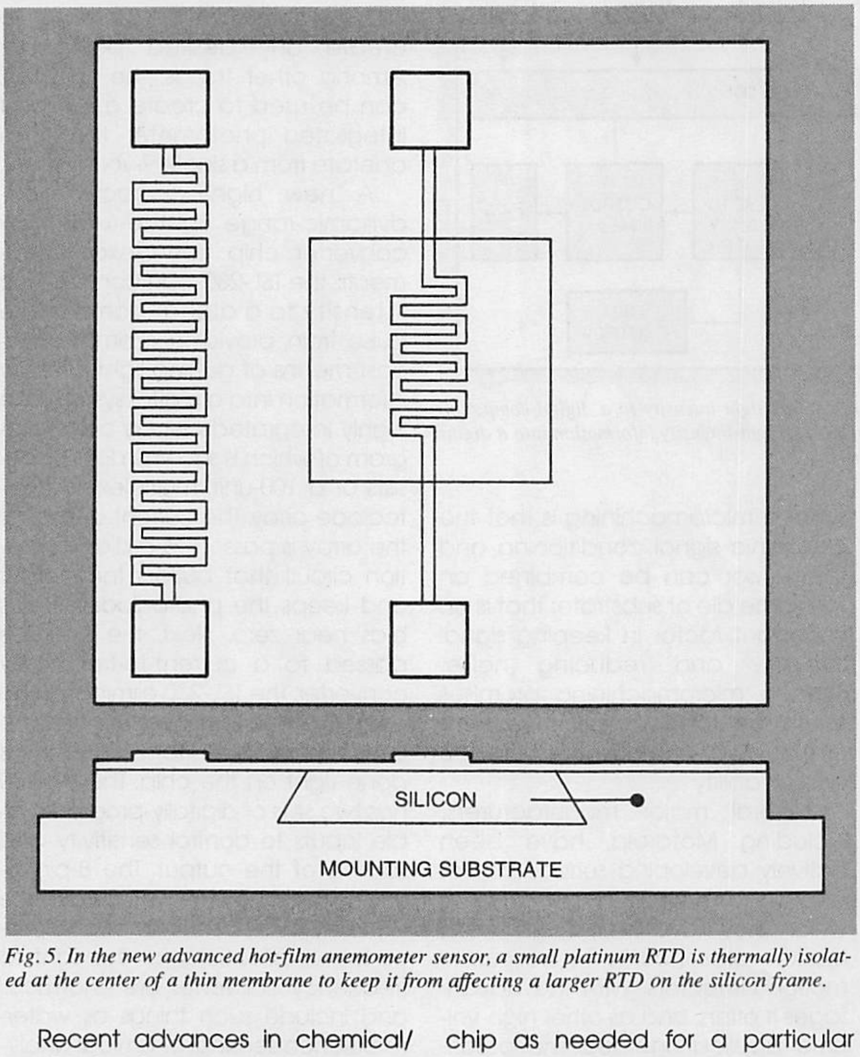


Fig. 5. In the new advanced hot-film anemometer sensor, a small platinum RTD is thermally isolated at the center of a thin membrane to keep it from affecting a larger RTD on the silicon frame.

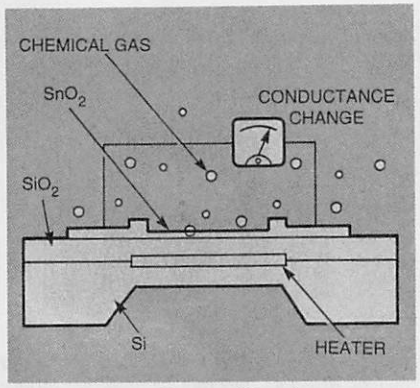


Fig. 6. Just as with its traditional counterparts, the micromachined gas sensor works by measuring changes in conductivity in a silicon-dioxide layer caused by the presence of a chemical gas.

Recent advances in chemical/optical micromachining have made it possible to fabricate optical components out of silicon to create an optical "bench" on a chip. Micro lenses, fresnel lenses, tunable filters, beam splitters, photodetectors, lasers, and LEDs can all be fabricated and combined together on a chip as needed for a particular application. Micro lenses have been built down to one-third of a millimeter or 0.013 inches across. Applications for the micro-optical "bench" include holography and interferometry. The "micro-bench" is extremely strong and rigid for its size, and because it does not have the mass of large optical mounts and tables, vibrations dampen out quickly.

Pressure Sensors. Motorola, a leader in semiconductor technology, has created the MPX-2000 series of pressure sensors, which use a piezo-resistive strain-gauge ion implanted on a thin silicon diaphragm. The highly integrated MPX-2000 also contains electronic signal conditioning and auto-calibration, all on the same chip. Excitation current is passed longitudinally through the piezo resistor. The pressure that stresses the diaphragm is applied at a right angle to the current flow. That stress establishes an electric field in the piezo-resistor that is sensed as an output voltage. Since the strain gauge is an internal part of the silicon diaphragm, there are no adverse temperature effects due to differences in thermal expansion, a common problem among older pressure sensors, These pressure sensors are available in three types: gauge, absolute, and differential.

Accelerometers. Silicon micromachining has also permitted the development of various types of piezoelectric and capacitive accelerometers whose performance closely matches that of more expensive servo accelerometers. Micromachined capacitive accelerometers are readily available to measure static phenomena, and are ideally suited to sensing the slow-motion movement created by building flex and bridge movements; their DC characteristic makes them highly effective inclinometers as well.

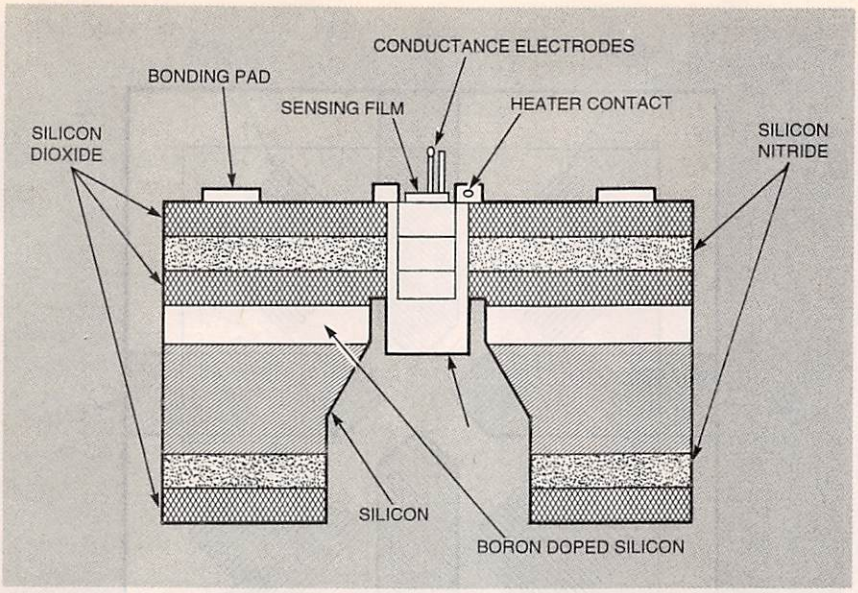


Fig. 7. A technology pioneered by University of Michigan researchers allows the creation of very thin, precise films in a small area. The highly selective deposition process allows for a wide variety of different sensitive films to be easily incorporated in a single device or in a cluster of sensors.

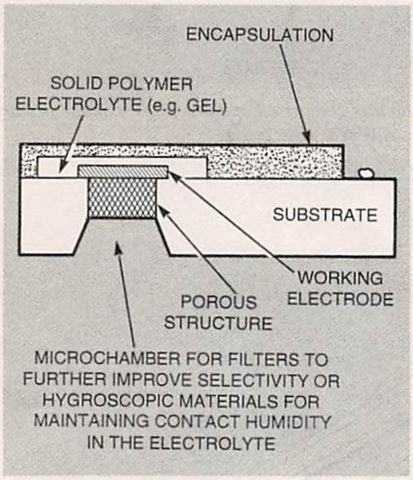


Fig. 8. This back-cell micro-electrochemical gas sensor consists of a substrate material with an opening across which a gas-permeable sensing electrode is placed. The front side of the electrode is coated with an electrolyte, and the gas diffuses from the back side.

Micromachined capacitive sensors (see Fig. 3) are built of three layers of silicon and two of glass fused together. The center layer forms the seismic mass, which is suspended by two cantilever beams. The seismic mass is located symmetrically between two plates, which act as electrodes. As the mass moves under acceleration it changes the position between the plates and therefore causes a change in capacitance. A block diagram of the integrated signal-conditioning electronics is shown in Fig. 4. The output produced by that circuitry is an analog signal that is proportional to the acceleration. Eventually, the high integration, low weight, and low cost of such micromachined accelerometers will most likely make older, bulk-machined accelerometers obsolete.

Tilt Sensors. In the past, tilt sensors were electrolytic; as such, they were slow to respond and suffered from considerable "slosh' noise" due to moving liquid. However, new, dual-axis tilt sensors from Crossbow Technologies make use of the accelerometer technology outlined in the previous section to produce a digital tilt sensor that provides excellent accuracy and frequency response, and can withstand 1000g shock forces. The new digital tilt sensor consists of two micromachined accelerometers, a temperature sensor, an A/D converter, and a microcontroller.

RTDs. Platinum thin films over micromachined silicon are now the medium of choice in the design of high-performance resistance-temperature detectors (RTDs), anemometers, and chemical gas sensors. Platinum-film micromachining has also been applied to the design of surface acoustic-wave (SAW) sensors, vibrating cantilevers, and micro actuators. Platinum wire and film have long been recognized for their near linear resistance *vs.* temperature relationship and wide temperature range. The ability to accurately measure temperature by measuring resistance is at the heart of many traditional and advanced RTDs.

Heat flow occurs whenever a difference of temperature exists between two points and continues until those two points reach thermal equilibrium *i.e.* the same temperature. If the temperature difference is held constant, the thermal transport between two points is also constant. Sensor design now becomes a matter of isolating a particular heat-flow mechanism and making the associated temperature measurements sensitive enough to observe changes in the heat flow. The thermal-transport balance equation is the focal point of some new platinum-on-silicon sensor designs.

Anemometers generally incorporate two RTDs. The temperature of one RTD is raised by resistive heating while the other RTD is held at ambient room temperature. The power needed to keep the temperature difference constant is thus a measure of heat loss due to conductive flow.

To work well, the hot RTD must be thermally isolated from the ambient RTD. That requirement has posed a number of heat-flow-control and packaging problems. For example, in the new advanced hot-film anemometer sensor, a small platinum RTD is thermally isolated at the center of a thin membrane to keep it from affecting a larger RTD on the silicon frame (see Fig. 5). That provides compensation for the temperature of the flow. The small heat capacity of the heated structure allows the sensor to respond rapidly to airflow changes. Using that same basic platinum on silicon design, it is also possible to create other types of sensors.

Gas Sensors. Some of the greatest advantages in new sensor design revolve around the sensing of gas and chemical species using thin-film micromachined technology. Traditionally, gas sensors use a heating wire that is covered with an insulating layer, which in turn is covered by a thin layer of tin dioxide. When the tin-dioxide layer is heated (by the interior wire), any reducing or oxidizing gasses present react with the absorbed oxygen on its surface and produce measurable changes in conductivity in that layer. The conductivity is monitored via a set of gold-plated electrodes. That basic technique is used for sensing hydrogen, carbon dioxide, methane, propane, and organic solvent vapors.

Figure 6 illustrates a micromachined sensor based on the same principle. It uses a micromachined membrane with a thin-film suspended heater element. The gas sensor consists of a micromachined thinned section of silicon, a heating circuit, an insulating silicon-dioxide layer, and a tin-dioxide sensing layer. The gas sensor integrates separate heating and temperature sensing elements as silicon circuits in the silicon membrane. One of the chief benefits offered here by thin-film and micromachining technology is that it allows operation at lower temperatures, hence greatly reducing power requirements. Older gas-sensor technology consumed $^1/_2$ to 1 watt of power in its heating element.

One of the most recent developments in gas sensors, pioneered by University of Michigan researchers, uses the idea of an integrated heater to perform a post process anneal on the thin film, essentially removing the film formation from the IC process itself. The integrated heater is used under the CVD-built thin film as a local heat source, which creates a small thermal mass. This process allows the creation of very thin, precise films in a small area; see Fig. 7. Heating the film to 1000°C can be accomplished in milliseconds due to the small area. The highly selective deposition process allows for a wide variety of different sensitive films to be easily incorporated in a single device or in a cluster of sensors. One of the design objectives was to create an integrated cluster of sensors that can combine temperature, gas, and humidity sensing on a credit-card-sized package that can be used by troops in the field to monitor the environment on a battlefield.

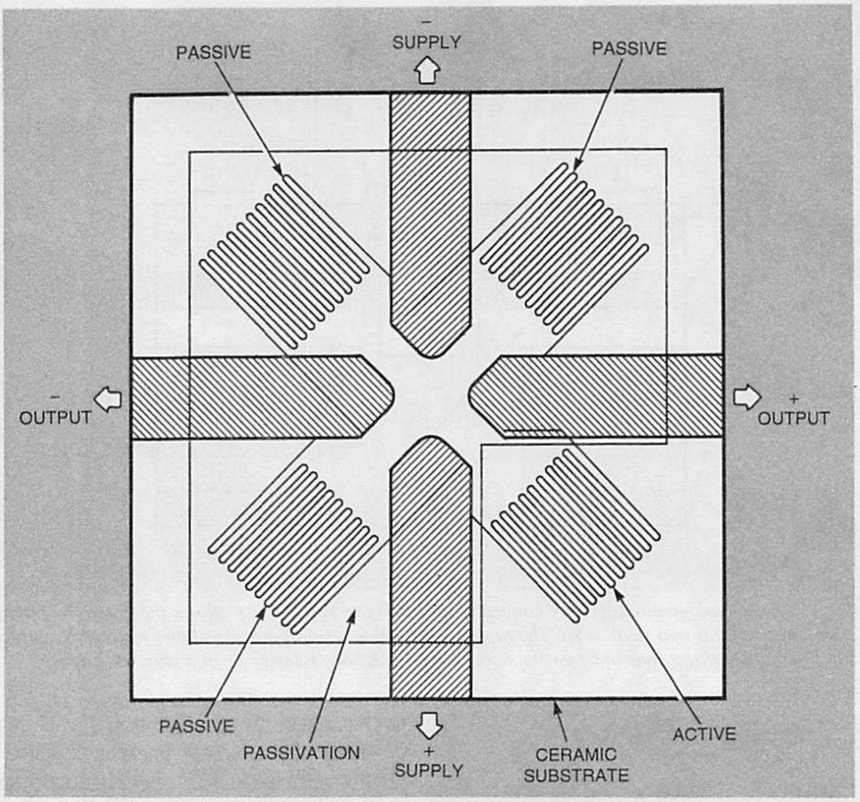


Fig. 9. In this hydrogen-palladium gas sensor, which is comprised of thick films, conductors are deposited as a serpentine pattern and connected as a Wheatstone bridge.

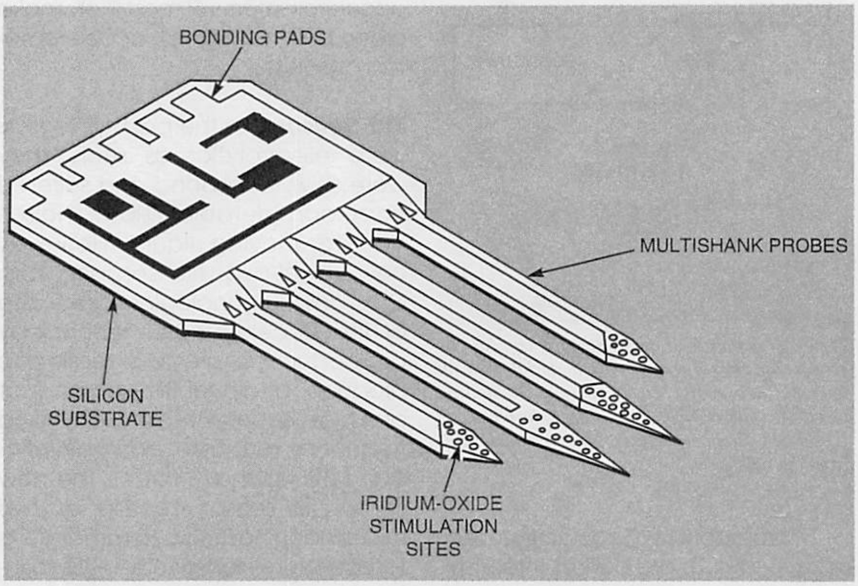


Fig. 10. This neural probe consists of bonding pads, highly integrated CMOS circuitry over a silicon substrate, and multi-shank iridium-oxide probe pins.

Teknetron has recently developed a back-cell micro-electrochemical gas sensor that consists of a substrate material with an opening across which a gas-permeable sensing electrode is placed. As shown in Fig. 8, the front side of the electrode is coated with an electrolyte, and the gas diffuses from the back side. The design is unique in that the material to be detected can diffuse directly to the electrode without having to bridge a long liquid path. The result is a linear response-time that's an order of magnitude faster than traditional electrochemical sensors. This new micro design is vastly superior to the older electrochemical gas sensors and uses a thick electrolyte layer of

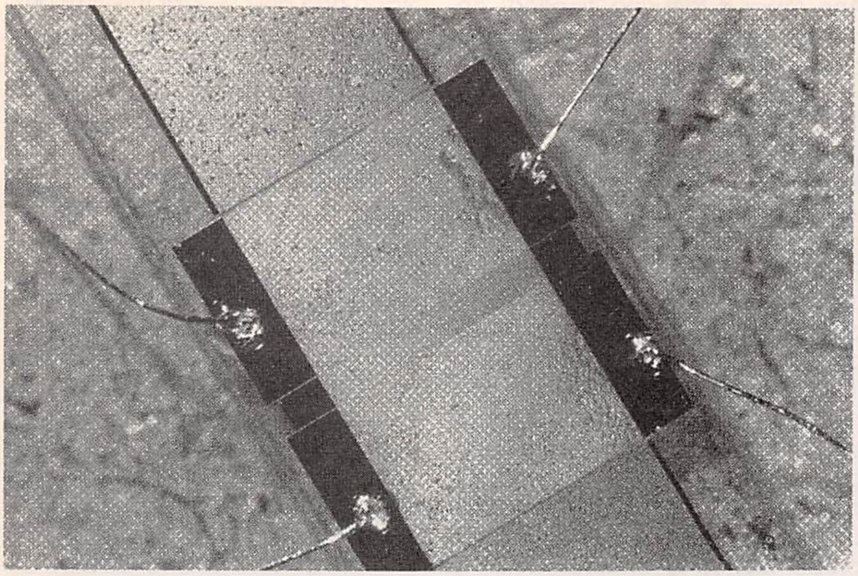


Fig. 11. A molecular-engineered, cyclodextrin-coated surface acoustic-wave micro sensor.

Nafion film, which is suitable for measuring a wide range of gasses, including oxygen, carbon dioxide, and carbon monoxide. Other new devices, which make use of calcium or yttrium-stabilized zirconium sensors, work by detecting voltage or current changes caused by gasses in contact with the solid electrolyte. Those types of sensors are used primarily in fuel-combustion control systems to determine air/fuel ratios.

A new group of low-power hydrogen sensors relies on the solubility of hydrogen palladium. Hydrogen molecules dissociate at the palladium/metal surface, and atomic hydrogen is absorbed until equilibrium is reached. That phenomena can be measured as a change in resistance in palladium. The new experimental hydrogen sensor is comprised of thick films. Conductors are deposited as a serpentine pattern and connected as a Wheatstone bridge. The thick film sensor is printed with a palladium paste on the first of four layers. The second layer is a gas-sensitive layer deposited as four identical serpentine patterns; see Fig. 9. The third layer is four individual segments that link the four sensor legs. The fourth layer consists of a twice printed passivation coating. Key features of the new hydrogen sensor are low cost, small size, and reduced power consumption. The target is to reduce power further and incorporate signal conditioning in the same package.

ChemFETs, or chemical field-effect transistors, are another new type of gas sensor. A chemically sensitive layer is placed onto the gate of an FET. Palladium, which is sensitive to hydrogen and hydrocarbons, is typically used as gate material. Thus the gates can be altered to target different gasses such as carbon monoxide and methane. ChemFETs can sense multiple species and could ultimately be produced cheaply. The limitations at present include poor selectivity and membrane adhesion. New research is also being done on ISFETs, or ion-sensitive field effect transistors. Lanmuir-Blodgett (LB) films or fatty acids that form a monolayer when spread on water are possible choices for use as ion-sensitive gate layers for these new FET gas sensors.

A research team in England has recently developed an array of 12 tin dioxide gas sensors with remarkable sensitivity. Each sensor in the array is slightly different from the other, and, using combinations of the 12, researchers have been able to train the array to distinguish between several varieties of tobacco smoke, the aromas of five types of alcohol, and a number of different blends and roasts of coffee. Classical pattern recognition, algorithms, or neural-network techniques interpret the pattern of the sensors' electrical resistance changes. This surrogate "nose" must first be trained by exposing it to specific concentration of known chemicals. The sensor responses are then stored and later compared with signals derived from sniffs or samples of unknown but related gasses.

Smart Sensors. Highly-integrated and advanced smart sensors are a hot topic in the control and process-technology arena. That interest is driven by the need to communicate information about processes or environments within a distributed control system. Integration technologies have allowed these new sensors to become microsystems in themselves, often incorporating sensor, signal-conversion microprocessor, memory, calibration, digital protocol, and communication features. The result is an advanced smart sensor with appropriate decision-making capability that can act as a stand alone sensor and communicate in a peer-to-peer relationship with other sensors in a large process or control subsystem. Smart sensors generally incorporate a ROM that stores the necessary information to allow the sensor to act as an intelligent node in the system and to identify and characterize itself over a two or three wire system.

Already there are a number of competing network protocols for smart sensors. The Lontalk system has been used in building automation systems as well as in automated toll booths. The CAN protocol developed by Bosch automotive is currently used in vehicle and industrial control applications. Honeywell is offering its SDS system. Control giant Allen-Bradley is marketing its Device Net protocol sensor technology. Dallas Semiconductor has introduced its low-cost, tiny, three-lead DS2407P two-channel addressable switch, which can be used to report temperature, vibration, and alarm activity in their MicroLan distributed network.

Medical Sensors. The medical industry has embraced advanced sensor technology and many applications are emerging. To date, the most widely used medical micro sensor has been the disposable pressure sensor. Micro pressure sensors have been used in a number of devices ranging from blood-pressure monitors, inter-uterine pressure transducers, infusion pump monitors, as well as kidney-dialysis machines.

The micro-miniaturization of chemical sensors and instruments is bringing about a revolution in instrumentation. Thin-film and micromachining technologies, along with advances in silicon semiconductor circuitry, have resulted in miniature sensing devices whose performance is equal to and in many cases better than their full size counterparts. Miniature massively-parallel sensing arrays with highly integrated electronics may eventually replace full-sized laboratory instruments.

By creating a "chemistry lab on a chip," researchers will be able to truly create hand-held devices to diagnose patients' diseases in the doctor's office. To accomplish such Herculean tasks, researchers are using every trick in the thin film and micromachining book.

I-Stat Corporation of Princeton, NJ has developed a hand-held blood-chemistry-analysis system. Conventional blood-chemistry analysis involves drawing blood, sending the samples to a lab, and waiting hours or days to get the results. The new hand-held blood-analysis instrument contains a series of cartridges. The instrument itself contains all the cartridge-interface sensing electronics, display, keyboard, and actuators necessary to operate the fluidic components. Each cartridge contains a silicon-based chemical-sensor chip, a sealed packet of calibration solution, and various fluid channels and chambers molded into the plastic cartridge. In operation, a sample of blood is introduced into a port in the cartridge and inserted into the instrument. The instrument punctures the seal of the calibration packet, causing the solution to flow over the sensor chip. Once calibration measurements are made, the blood sample flows over the chip in place of the calibration solution. The instrument then records and displays the measurements. Measurements are made in just a few minutes, making this instrument well suited for emergency situations.

The University of Michigan at Ann Arbor is focusing its efforts on the development of an implanted biomedical microprobe. The silicon microprobe is designed to interface with the body's central nervous system at a cellular level. If inserted in the brain, electrodes within the device can record electrical firing patterns of the neurons. Effectively that would allow for compensation of neural deficits and could be used to help provide control of natural or prosthetic limbs in paralyzed patients. The neural probe, shown in Fig. 10, consists of bonding pads, highly integrated CMOS circuitry over a silicon substrate, and multi-shank iridium-oxide probe pins. The microprobe device is fabricated using deep boron diffusion techniques, and is typically 15-μm thick. The active microprobe can be used for recording activity at, and stimulation of, a tissue site.

SAW Sensors. One of the most popular chemical sensing devices is the SAW, or surface acoustic-wave sensor. A SAW sensor consists of a piezoelectric film coated with a thin film that allows selective rejection or retention of a specific species for a variety of mixtures. After the thin-film material has been applied to the piezo surface, a transducer delivers a surface acoustic wave of a known frequency. The thin-film coating acts as molecular "flypaper" that increases the mass of the device if certain gasses are present. That causes the baseline frequency of the surface acoustic wave to shift to a new, lower constant level that is correlated to the presence of a selected sample.

For example, a modified SAW sensor labeled the Enviro-SAW uses a thin organic membrane for selective retention of PCBs. The front end of that system consists of a sampling device and a catalytic filter to reduce the amount of noise introduced by heavy organic compounds, such as sludges and oils. Integrated electronics for the SAW sensor and data collection are controlled by a laptop or desktop personnel computer.

The new SAW sensing devices need only $1/_{10}$ the sample volume of a laboratory GAS chromatograph and only $1/_{1000}$ of the amount needed for immunoassay systems. Surface acoustic wave sensors can be used for other types of applications, such as monitoring hydrogen gas levels.

Another recently created SAW device is capable of conducting remote real-time sensing of volatile organic compounds in air, water, and possibly soils. That SAW device relies on molecular self-assembly technology, which allows toxin sensing molecules to self-assemble so that one end of the molecule covalently bonds directly to a sensing detector while the other end extends as a bucket tailored to temporarily trap specific chemicals. Changing the size and polarity of the bucket allows the micro sensors to be chemically and structurally tuned to optimize their sensitivity and selectivity to specific toxins. The buckets are constructed using molecular-engineered cyclodextrin, a component of starch that traps organic toxins but doesn't bind them. A molecular-engineered, cyclodextrin-coated surface acoustic-wave micro sensor is shown in Fig. 11.

Other Developments. A recently developed glass microchip sequentially performs chemical reactions and capillary electrophoresis. That device, shown in the photo at the beginning of this article, could provide faster, less-expensive, and more-reliable chemical analysis for environmental monitoring, medical diagnosis, and process control. That postage-stamp sized sensor uses a hair-like capillary channel etched into the glass using standard micromachining techniques. The channels are closed and formed into capillary tubes by bonding a thin plate of glass over the etched tubes. Reservoirs for buffers, reagents and waste are also bonded into the chip. That type of sensor promises to reduce the amounts of samples and reagents consumed, use less power, and perform faster—chemical separations in the sensor can be carried out in 150 ms—than before possible using standard laboratory analysis. It is also inexpensive to produce.

At Lawrence Livermore Lab, a

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miniaturized polymerase chain-reaction instrument, or PCR, has been created. The miniature PCR, which is actually a miniature chemical reactor, is machined from three components: a single silicon crystal, which acts as an efficient heat sink; a low-stress silicon nitride, which acts as a chemical passivation layer and a window for viewing the reaction with fluorescence detection; and doped polysilicon, which acts as a miniature heater. Among other things, that new device could be use for forensic analysis, genetic engineering, clinical diagnostics, and environmental contaminant/pathogen detection.

Advances in micromachining have created miniature gas chromatographs or GC sensors, which create the basis for an amazingly powerful handheld instrument capable of operating up to 20 times faster than its larger laboratory counterparts. In the past an immunoassay could take up to 30 minutes to perform, while the miniature micro GC can complete the exact same measurement in less than 10 minutes.

A chemist at the University of California at Berkeley has constructed a miniaturized electrophoresis gel instrument, which at 25mm by 50μm, is fifty times smaller than slab gels used in conventional instruments. This "gel on a chip," which is shown in the photograph at the beginning of this article, is the first step in building a micro chemical-analysis system where DNA could be put on a chip, amplified, loaded into a capillary array, detected, and analyzed all in one step. This is truly chemistry on a chip at the micron level.

As impressive as the advances outlined here are, smart-sensor technology is still in the embryonic stages of its development. The future for this exciting field is virtually unlimited, and could well make possible technologies and devices that heretofore have belonged only in the realm of fantasy and science fiction. Ω