SENSORS

1. Introduction

Sensor technology is being revolutionized by advances in microelectronics and optoelectronics. The newer sensors are demonstrating improvements in the operation, reliability, safety, and efficiency of many engineering systems. Perhaps the most familiar consumer example of this technology is found in automobiles, where silicon-micromachined pressure sensors, coupled to an electrochemical oxygen sensor, allow the engine management computer to provide the correct fuel and spark parameters for smooth, low pollution operation. Some automobiles include rotation rate sensors for antilock brakes, fluid flow sensors for gas mileage computation, accelerometers for air bag deployment and antiskid operation, proximity sensors for anticollision and temperature sensors for closed-loop temperature control of the passenger area. Development of other sensors for safety, comfort, and pollution control are underway.

Increasingly, the word sensor is used interchangeably with, or in place of, the word transducer to represent the conversion of one type of energy into another. The word actuator, however, refers to a distinctly different set of devices capable of activating a device upon receiving an appropriate signal. Sensors and actuators may be found as part of a system on a single piece of silicon.

Sensor systems of the new century almost always include data acquisition capabilities. Because of the low cost of computers, microprocessors, analogue–digital converting circuit boards, and other peripherals, the concept of large arrays of distributed sensors has become commonplace. The sensor itself is often the weak link in such a system, partly because the investment in sensor technology has been dwarfed by the development of microelectronics technology, but also because of fundamental differences in the nature of the problem. Personal computers deal with a relatively limited set of physical variables, ie, principally the flow of electrons through semiconductors and metals. With the exception of some impressively precise and sophisticated electromechanical engineering for disk drives and printers, the means of computer input and output are relatively minor extensions of extremely well-developed technologies: the typewriter keyboard, the cathode ray tube, and sometimes audio speakers.

In contrast, various sensors are expected to respond in a predictable and controlled manner to such diverse parameters as temperature, pressure, velocity or acceleration of an object, intensity or wavelength of light or sound, rate of flow, density, viscosity, elasticity, and, perhaps most problematic, the concentration of any of millions of different chemical species. Furthermore, a sensor that responds selectively to only a single one of these parameters is often the goal, but the first attempt typically produces a device that responds to several of the other parameters as well. Interferences are the bane of sensors, which are often expected to function under, and be immune to, extremely difficult environmental conditions.

Although it is possible to obtain, manipulate, display, and act on huge amounts of data, the degree to which such data are meaningful often hinges on the reliability of the sensor itself. The pervasiveness of inexpensive microprocessors has also freed sensor technology to exploit phenomena that give logarithmic and other nonlinear responses to measurands. In some commercialsensors, the calibration curves for the individual sensors are storedin an embedded memory chip so that when the sensor is plugged into a system the correct sensor values are transmitted automatically. This standard is now called TEDS (Transducer Electronic Data Sheet) following the IEEE P1451.4 standard. One problem not solved as of 2005 by computer technology (qv) is a sensor output that is not repeatable or predictable (eg, due to baseline drift or change in sensitivity). Automated or automatic calibration is a partial solution to this problem, however, manual recalibration against standards is commonly used to correct this problem.

In the field of chemical sensors, the revolution in software and inexpensive hardware means that not only nonlinear chemical responses can be tolerated, but incomplete selectivity to a variety of chemical species can also be handled. Arrays of imperfectly selective sensors can be used in conjunction with pattern recognition algorithms to sort out classes of chemical compounds and their concentrations when the latter are mixed together. These arrays are sometimes called "electronic noses" and there has been considerable recent research interest in them (1). Since Sept. 11, 2001 there has been a new urgency in the developement of sensor technology, particularly chemical sensors, driven by homeland security concerns. The inadequecy of portable anthrax detection technology was demonstrated by the mail anthrax attacks. The detection of explosive devices, particularly at a distance, is being emphasized, as is the detection of chemical weapons in R&D programs. Although progress in improved technologies for these areas is promising in 2004, much remains to be done to protect us from these kinds of attacks.

2. Decision-Making Tool for Sensor Technology

The rapid advances in sensor technology have increased the difficulty of the task of finding the best sensor system for a given application. Figure 1 shows a flow chart designed to be used as a decision-making tool for sensor technology (2). The sensor customer or engineer needs to be specific about defining the sensor problem to be solved, using language and descriptors that are commonly shared between the customer and a sensor technologist. An extensive sensor glossary and set of sensor descriptors is available (2). A sensor technologist or a sensor buyer's guide such as the annual guide produced by *Sensors Magazine* (3) can be a great help in locating vendors for various technologies.

Many physical principles can be employed by different sensor vendors to obtain the same measurement. For example, in 2004, 79 vendors were listed for hydrogen sensing (3). Represented among the sensor systems are mass spectrometers, gas chromatographs, electrochemical cells, thermal conductivity cells, Raman scattering instruments, metal-oxide semiconductors, and pellistor (catalytic material-coated wire) sensors. To the process of sensor selection, the engineer brings specifications such as cost, size, weight, sensitivity, selectivity, and lifetime. The engineer must also specify the environmental conditions to which the sensor system is to be subjected: high or low temperature, vacuum, corrosive chemicals, vibration, etc. The specifications can be cast in the form of descriptors and matched against each vendor's performance specifications. No common database for performance specifications is available as of this writing (~2004), and often the literature for each vendor must be compiled at a cost of much time and effort. Performance under hostile conditions is often not available, forcing the sensor engineer into a test program to verify the commercial sensor's performance. In many cases, all the commercially available sensor systems fail to meet the specifications, leaving the engineer with the choice of redefining the specifications or launching a development project to fabricate a sensor system that solves the problem.

Developing a new solution may take the form of a modification of sensors already available or using the sensor principles of an available sensor, but modifying it to meet the specifications. On the other hand, new principles and manufacturing techniques may be explored in a long-range project to yield improved sensor performance. There is a large and growing research and development (R&D) effort in sensor technology because many engineers see that the advances in microelectronics, optoelectronics, and biotechnology are pointing the way to sensor performance unobtainable with commercially available sensor systems.

An important part of the decision-making tool flow chart (see Fig. 1) is the redefinition of the specifications by the sensor customer after the surveying and testing of commercial sensor systems. This process almost always involves a downgrading of the expectations of the sensor customer, but it can also force a realistic evaluation of what sensor information really needs to be made available and at what cost.

In an era of inexpensive, batch-processed sensors, the concept of throwing away the sensor element, ie, the transducer, actually becomes cost effective. An example would be the miniature electrochemical cells on a paper test strip for monitoring blood glucose. The instrument for measuring the elctrochemical current may be relatively expensive, but each test strip costs only pennies, in spite of the apparent complexity of having screen-printed electrodes with a membrane containing dry glucose oxidase. Under long-time exposure to blood, this sensor no longer gives the calibrated electrochemical current level for values stored in the reader memory. Thus the sensor, not adequate for closed-loop control of an implanted insulin pump, is adequate for a quick, one-time reading of glucose in a fresh drop of blood.

Another important path on the flow diagram (see Fig. 1) is the short-term implementation of proven concepts. Often it is the packaging, not the sensor itself, that fails in the test environment. An old sensor may be improved by application of more rugged packaging, encapsulation, wiring, etc. When all else fails, however, the customer may have to fund longer-term directed research and development on unproven sensor concepts. The strategy for this kind of R&D involves a strongly interdisciplinary activity, combining materials science, electrical engineering, chemistry, packaging science, etc (2).

A good survey of many sensors can be found in the literature (4,5). A number of international journals are also devoted to new sensor technology (see *General References*). Sensor papers often appear in journals such as *Analytical Chemistry Journal of the Electrochemical Society*, and *The Journal of Applied Physics*. Several international conferences focus on sensors, most notably the biannual *Transducers: International Conference on Solid-State Sensors and Actuators*. Digests from the *Transducers* conferences are very good references to the state of the art. The Society of Photooptical Instrumentation Engineers (SPIE) conducts many sensor symposia and publishes proceedings volumes. Of course internet searches are becoming a faster method of gathering sensor information; every sensor vendor will have a webpage.

3. Sensors Based on Silicon Processing Technology

The art of batch processing has brought the silicon-based integrated circuit (IC) (see INTEGRATED CIRCUITS) and related electronic components to an almost unbelievably low cost. A digital watch, which could not be purchased at any price in 1970, could be had for < \$10 retail in 2004. The watch contains integrated circuits, a quartz crystal oscillator, a liquid crystal (LC) display, a battery, and the case. For a somewhat higher price, watches having sensors for temperature, barometric pressure, altitude, compass direction and global positioning data were available.

The tools for the revolution in new sensors include micromachining, batch processing, integrated sensors, readout and networking electronics, light-emitting and detecting structures, fiber optics (qv), etc. This revolution has led and is leading to new applications of old fields of science from mechanics to physical chemistry, fluid mechanics, electrokinetics, capillary action, etc. These principles are being applied in a micro/nano-scale world, where batch processing means inexpensive, rugged systems. Nanomaterials are under intense development and may provide sensor materials with unprecedented sensitivity and stability (6) (see NANOTECHNOLOGY).

The most commercially successful silicon-based sensors are the photodetectors (qv). These are found in video cameras, security systems, ionizing radiation detectors, and many other applications. Photodetectors, closely related to solar cells in the principles of operation, all depend on light and ionizing radiation creating electron–hole pairs in the semiconducting material. There are many ways that the presence of the excess number of electron–hole pairs can be monitored. The simplest is the observation of a change in electrical conductivity, ie, photoconductivity. Ingenious schemes involving the storage of photoelectrons or holes are used to make the very sensitive charge-coupled device (CCD) arrays.

There are also a large number of photodetectors made from semiconductors other than silicon. Gallium arsenide, GaAs, and its alloys are the most common because the wavelengths to which they are sensitive can be widely varied, and light-emitting sources such as light-emitting diodes (LEDs) and lasers (qv) can be made from the same materials (see LIGHT EMITTING DIODES). The compact-disk player is a good example of the common use of both a semiconductor photoemitter and detector.

One of the fastest growing areas of sensors based on silicon involves the use of micromachining to fabricate the sensor. The largest commercial markets are for micromachined pressure sensors and accelerometers. Chemical etching of the silicon is the key technology for the fabrication of these sensors. Isotropic etching refers to a process in which the etch rate of the materials is uniform in all directions. Anisotropic etching refers to etch rates that depend on the crystallographic orientation of the silicon wafer. Anisotropy ratios of 400:1 are possible for special directions. Doping of the silicon can have a large effect on the etch rate, and layers of different materials, such as SiO_2 and Si_3N_4 can have different etch rates. For pressure sensors, thin diaphragms of Si or related materials are etched into the wafer (see PRESSURE MEASUREMENT).

Many of the variations developed to make pressure sensors and accelerometers for a wide variety of applications have been reviewed (7). These sensors can be made in very large batches using photolithographic techniques that keep unit manufacturing costs low and ensure part-to-part uniformity. A pressure differential across these thin diaphragms causes mechanical deformation that can be monitored in several ways: piezoresistors implanted on the diaphragm are one way; changes in electrical capacitance are another.

A smart sensor is loosely defined as a sensing device with built-in intelligence that usually involves some kind of digital signal processing. Because the sensor is already being batch-fabricated on a silicon wafer, it seems natural to create the signal-processing electronics on the same chip as the sensor itself. Some devices based on this technology are commercially available. An advanced example is given in Fig. 2 (7). This pressure sensor is based on an anisotropically etched cavity, four piezoresistors that occupy the large square at the center of the chip, surrounded by digital electronics that correct the offset and sensitivity of temperature coefficients of the signal from the sensor along with other parameters. The calibration points are stored in a 30-bit static shift register, and the electronics needed for communicating the pressure values to a small computer are also integrated on the chip.

Pressure sensors that give temperature-corrected, linear, analogue voltage output are available from Motorola and other manufacturers. In such sensors, the on-chip electronics correct any temperature effects and nonlinearities in the output of the piezoresistors. The on-chip electronics replace a shoebox-size collection of printed circuit boards. The price of this kind of smart sensor is considerably $<\$100$. The integration of a large amount of circuitry on the chip allows functions like amplification, offset correction, self-testing, autocalibration, interference reduction, and compensation of cross-sensitivities (8).

The integration of standard integrated circuitry and a sensor is not always a trivial extension of the IC process, because the processing steps involved in fabricating the sensor may be incompatible with the correct functioning of the IC. An alternative is the hybrid package where the sensor chip and the signal-processing chip are fabricated separately and then glued together in the same package. There are a number of methods for connecting the leads from the sensor chip to the signal-processing IC. The hybrid method may be more expensive to package, but the integrated smart sensor may entail expensive and time-consuming process development to implement the ultimately less expensive final chip. Whereas sophisticated smart sensors like the one shown in Fig. 2 may appear to be a manufacturable device, the sensor may not be available for purchase by the sensor customer until a vendor steps forward and takes the responsibility for manufacturing, packaging, servicing, and sales.

Even the tight controls in silicon integrated circuit manufacturing are not yet sufficient to produce absolutely identical sensors on a single wafer. Calibration of the final product is usually necessary, often by adjusting the value of a circuit element on the IC such as a resistor. The calibration process can be automated, but it still adds to the cost of batch-fabricated sensors. Clever means of self-calibration, particularly in field use, are constantly being sought.

Silicon microelectronics are often touted as giving the most sensitive and stable measurements of physical phenomena, eg, charged particle detectors that can record a single X-ray photon or beta particle. In the realm of chemical detection, biological systems unequivocally outperform all of the microelectronically based chemical sensors in terms of sensitivity and selectivity. One of the best studied examples of biological chemical detection is the sex attractant receptor of moths. Single-molecule detection of the sex attractant molecule, bombykol, can be claimed if the firing of a single neuron by probes is monitored. However, if the response of the moth is the criterion, an airstream containing 1000 molecules/cm^3 or 1 part in 10^{16} at standard temperature and pressure is required (9). The moth's microsensor is a receptor on a membrane protein that is part of the ion channel in the nerve cell wall.

A silicon-based sensor that operates on a similar principle is the chemically sensitive field-effect transistor (ChemFET) (10–12). The channel through which the electrical current flows is a very thin ($\sim$10-nm) layer in the silicon crystal near a planar interface with an oxide of silicon that is thermally grown on the crystal. This interface has received an enormous amount of interest because it forms the basis for most active devices in integrated circuits. The very high sensitivity of the ChemFET is in part a result of it acting as a chemical amplifier. In these small devices, as few as 10^6 hydrogen atoms occupying interfacial sites can cause an order of magnitude increase in conductivity (12).

ChemFETs have been fabricated for the detection of a wide variety of chemical species. In the gas phase, catalytic metal gates (field plates) have been used to sense hydrogen, ammonia, ethanol, formic acid, ethylene, carbon monoxide, and many other molecules. Ion-conductive liquids, usually water, can also form the field plate, and pH-sensitive dielectric layers have led to commercially available pH sensors (see HYDROGEN-ION ACTIVITY). Other ions can also be detected by placing various kinds of ion-sensitive membranes on the dielectric. Detectors known as biosensors (qv) have been fabricated by placing membranes containing immobilized enzymes on the dielectric. These devices are often called enzyme-immobilized FET (ENFETs). An often-studied ENFET is the one that detects glucose. It usually works by immobilizing the enzyme glucose oxidase. The presence of glucose causes the production of gluconic acid in the membrane, and the pH change is detected by the FET (10–12).

4. Technologies Other than Silicon

Another emerging physical transduction technique involves the use of acoustic waves to detect the accumulation of species in or on a chemically sensitive film. This technique originated with the use of quartz resonators excited into thickness-shear resonance to monitor vacuum deposition of metals (13). The device is operated in an oscillator configuration. Changes in resonant frequency are simply related to the areal mass density accumulated on the crystal face. These sensors, often referred to as quartz crystal microbalances (QCMs), have been coated with chemically sensitive films to produce gas and vapor detectors

(14), and have been operated in solution as liquid-phase microbalances (15). A dual QCM that has one smooth surface and one textured surface can be used to measure both the density and viscosity of many liquids in real time (16).

Another class of acoustic wave sensors uses surface acoustic waves (SAWs) to probe the accumulation of species in a surface film. These devices use interdigital electrodes that are photolithographically formed on the surface of a piezoelectric crystal to excite and detect the surface wave. The stress-free boundary condition imposed by the surface results in a mode of propagation that is confined to the surface and has acoustic energy distributed within one wavelength of the surface. This surface confinement of acoustic energy makes the SAW extremely sensitive to the properties of a surface film, particularly changes in its mass. The surface wave has two components of displacement, one normal to the surface and one in the direction of wave propagation. It is the translation of surface mass by these SAW displacement components that leads to a change in surface wave velocity. Mass sensitivity can be further enhanced by propagating a wave in a very thin membrane (17), generating an acoustic mode known as a Lamb wave.

The acoustic wave gravimetric technique can be extended to liquid-phase sensing in one of two ways. Because the SAWs surface-normal displacement component generates compressional waves in a contacting liquid, excessive attenuation of the SAW occurs, rendering it unsuitable for liquid-phase measurements. A mode having exclusively in-plane surface displacement, such as the shear-horizontal acoustic plate mode, can, however, be used successfully (18). Shear waves propagate poorly in liquids, so attenuation is minor. The quartz thickness-shear resonators described also have no surface-normal displacement and thus function in contact with liquids. A second alternative is to use an acoustic mode of velocity slower than that of sound in the contacting liquid, such as the Lamb wave, which is described in detail in the literature (17).

A number of gas and vapor sensors have been realized by placing chemically sensitive films on SAW devices and relying on their extreme mass sensitivity. The first such sensor, reported in 1979 (19), detected a range of organic vapors utilizing thin films of vacuum grease, oils, and waxes commonly used in gas chromatography (qv). More than 100 papers have been published in this field since that time, including several reviews (20,21). Some of the most intensely studied areas include the use of organic polymer films to detect organic solvent vapors (22–25); monitoring small inorganic molecules, such as the halogens, NO_x, and sulfur oxides, using organometallic films, eg, metal phthalocyanines (26,27) or metal oxides (28); humidity sensors based on organic polymer films (29,30); and the detection of organophosphonates, simulants for and decomposition products of chemical warfare agents (31,32), using a variety of different thin-film materials. Styrene has been detected by its reversible reaction with an organoplatinum compound (33).

Optical fibers offer a number of advantages for chemical and physical sensing (34). This technology offers long-distance telemetry, freedom from electromagnetic interference, and small size, ie, approximately that of a human hair. Furthermore, the basic components necessary for sensor applications are being developed by the optical communications industry. Indeed, optical communications systems and optical sensors have the same functional design. Both need a light source, a detector, and a method of transmitting the light from the source and to the detector, namely, the optical fiber. For optical communications, a modulator is used to impose the information to be transmitted on the light beam. For optical sensing, the sensing element replaces the modulator and again imposes information on the light beam.

The sensing element can modify either the intensity, phase, or polarization state of the light, and physical sensors have been made that make use of all three techniques (35,36). For chemical sensing, most transduction mechanisms have focused on intensity modulation. Spectroscopy and fluorescence-based fiber optic sensors are in this group. A small effort (37) has been aimed at utilizing phase-modulating sensors, ie, interferometers. The development of fiber optic chemical sensors has been slower than other chemical and physical sensing techniques. Research in the field performed by members of the Society of Photooptical Instrumentation Engineers (SPIE) is recorded in their annual Chemical, Biochemical, and Environmental Fiber Sensors symposium.

The most successful chemical microsensor in use as of the mid-1990s is the oxygen sensor found in the exhaust system of almost all modern automobiles (see EMISSION CONTROL, AUTOMOTIVE). It is an electrochemical sensor that uses a solid electrolyte, often doped ZrO_2, as an oxygen ion conductor. The sensor exemplifies many of the properties considered desirable for all chemical microsensors. It works in a process-control situation and has very fast ($\sim$100 ms) response time for feedback control. It is relatively inexpensive because it is designed specifically for one task and is mass produced. It is relatively immune to other chemical species found in exhaust that could act as interferants. It performs in a very hostile environment and is reliable over a long period of time (38).

The success of the O_2 sensor has made the auto manufacturers, regulators, and environmentalists anxious to extend chemical sensing to a variety of tailpipe gases, notably CO, NO_x, and short-chain hydrocarbons. Considerable research and development is needed for these molecules to be monitored in the hostile exhaust system environment (38).

Ion-selective electrodes and amperometric cells have had a long history of success in a wide variety of applications (10,11,39,40). A microelectronics-inspired revolution is also occurring in these devices, brought about by the advent of photolithographically defined arrays of microelectrodes on planar substrates (41).

Another kind of conductometric sensor that is commercially available and has growing sales is formed from ceramic semiconducting metal oxides. The most common type of sensor consists of a thin porous film of tin oxide, SnO_2, deposited with a heater and electrodes to monitor the metal oxide conductivity. These sensors are often called Taguchi gas sensors, after the inventor. They are primarily used in small stand-alone sensor packages for detecting hazardous gases such as carbon monoxide and natural gas, ie, methane and butane, leaks. The mechanism for the change of conductivity in the presence of these reducing gases involves oxidative and reductive chemical reactions at the exposed surface and near-surface regions of the metal oxide. The dopant that makes these wide band gap materials semiconducting is actually a missing oxygen in the lattice, ie, a vacancy. Because of the porous and heterogeneous nature of the ceramic films, there is still considerable debate about the roles of various surface reactions in the sensing response. Typically, the ceramic must be quite hot (>200°C) to operate quickly and reversibly. The history, principles of operation, and performance data for the tin oxide-based sensor have been described (42). Many other metal oxide semiconductors have been investigated for their gas-sensing properties, and a vast literature exists describing many preparation procedures, the addition of catalysts, the integration of the metal oxide film on silicon microhotplates, etc. This literature shows a large development effort to overcome the shortcomings of this type of sensor, which include poor selectivity, in which some home CO detectors based on this technology can sound false alarms for nail polish, various polishes and cleaners, and ethanol; large power consumption, in which the same home CO sensors are invariably powered from the alternating current (ac) power lines, not batteries; problems with consistency in manufacturing; lack of a stable baseline; etc (42).

5. Economic Aspects

Sensors form a very broad-based, multibillion dollar business. Detailed information and predictions of the growth in the many sensor subfields can be found in the literature (43). For example, the relatively narrow area of acceleration and vibrations sensors was a $600 million business in 1995 and projected to become a > $1 billion business by 2008. New applications, often driven by regulatory and safety concerns as well as homeland security, mean projected growth of just about every sensor type.

Sensors based on microelectronics and photonics advances, along with gains in materials and interfacial science, are certain to provide higher performance sensor systems. The feasibility of much higher performance in terms of size, power consumption, and selectivity than that available as of the new mellinium is demonstrated by biological sensors. The revolution in microelectronics manufacturing technologies nevertheless shows a growing trend toward diminutive cost as well as size. There is much current interest in wireless sensor networks. While this is mostly driven by the spectacular advances in cell phone and other radio frequency (rf) communication technologies, the sensors must be small and reliable to make the network perform properly. In the particularly difficult case of chemical sensing, considerable development is expected to be necessary in order to match the sensing abilities of an animal, such as a dog, to pick just one familiar example, but progress in that direction is expected.

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Robert C. Hughes
A. J. Ricco
M. A. Butler
S. J. Martin
Sandia National Laboratories