Sensors: Engineering Structures and Materials from Micro to Nano

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Sensors science and engineering is relevant to virtually all aspects of life including safety, security, surveillance, monitoring, and awareness in general. Sensors are central to industrial applications being used for process control, monitoring, and safety. Sensors are also central to medicine being used for diagnostics, monitoring, critical care, and public health. This article is a brief introduction to world of sensors.

Sensors are devices that produce a measurable change in output to a known input stimulus. This stimulus can be a physical stimulus like temperature and pressure or a concentration of a specific chemical or biochemical material. The output signal is typically proportional to the input variable, which is also called the measurand. For example, temperature sensors respond with a voltage, resistance, color, or other change when the temperature is changed. Sensors can be used in all three phases of matter although gas and liquid sensors are the most common. Sensors are transducers, in that the incoming property to be measured, *e.g.*, temperature, is changed or transduced by the sensor into an electrical or other convenient output for the user. The thermostat in your home takes temperature and turns it into mechanical motion by unfolding a bimetallic strip that turns a dial calibrated to read in units of temperature. In this way, the thermal energy associated with a specific temperature is transduced into mechanical motion.

Generally, sensors can be divided into three major categories: (*i*) physical sensors for properties like *T*, *P*, flow, stress, strain, position, particles, or force; (*ii*) chemical sensors for concentration or identity of a chemical substance like ethanol, carbon monoxide, gasoline, or other molecules; and (*iii*) biosensors for biologically active substances be they cellular like toxic plague bacteria or anthrax spores, supramolecular like flu viruses, or molecular like protein toxins like *Staphylococcus enterotoxin B* (SEB). Sometimes biosensors are considered a subset of chemical sensors. New nanotechnology and novel materials provide exciting contributions to sensor technology.[1]

There are six sensor classes typically divided by the energy transduced in the sensor. These are optical, mechanical, thermal, magnetic, electronic, and electrochemical sensors. This division is illustrated in Fig. 1 wherein the electronic and electrochemical sensor classes are combined for convenience, and because they are often related and integrated. For example, in an optical class chemical sensor, the presence of a chemical stimulus modulates an optical property of the sensor providing a change in optical signal (intensity or wavelength of light). There is not a single sensing class or technology that can effectively detect everything of interest in every possible environment. Rather, selecting the optimum sensing approach from a group of technologies may be the best method to address a sensing need. There are a range of sensor types to choose from, *i.e.*, within the electronic and electrochemical sensor classes, the possible sensor platforms include Schottky diodes, metal oxide semiconductors, electrochemical cells, and calorimetric devices.[2] A given sensor can therefore be described from the target analyte viewpoint – sensor for CO hydrogen or ethanol; or from the platform viewpoint – surface acoustic wave (SAW) sensors, electrochemical sensors, or optical sensors, mass based sensors, or nanowire sensors.

Many newer sensors are built by microfabrication techniques and this provides a host of advantages including lower power consumption, small size, and light weight.[3] These microfabrication techniques can be used to produce a range of different basic microsensor platforms. These microplatform structures can be tailored to optimize its use for a given detection problem. For example, the microfabricated pattern for an electrochemical cell to detect gases can be formed and repeatedly fabricated. However, varying the selection of electrolyte and electrodes to be deposited in the microstructure can result in very different gas sensor types. Figure 2 shows, in effect, a family tree of sensor platform approaches and the wide range of sensor types and measurement options which can result from using these platforms.[2] Each chemical microsensor platform has it own strengths, ideal range of application, and provides different types of information about the environment. For example, different sensor platforms have different responses to the reactant gas (*e.g.*, exponential, logarithmic, power law, etc.). Which sensor class, platform, or combination of platforms one uses, and how those sensors are tailored, depends on the needs of the application. Considerations include:

1. Does the application require high sensitivity or a broader range of detection?
2. Can the application needs be met by careful choice of the operating parameters of the sensor or will a combination of technologies be needed to sort out the contribution of various similar analyte?
3. Does the application's operating environment require special materials or fabrication procedures?

The ECS Sensor Division typically is concerned with the topic areas of chemical and biochemical sensors and

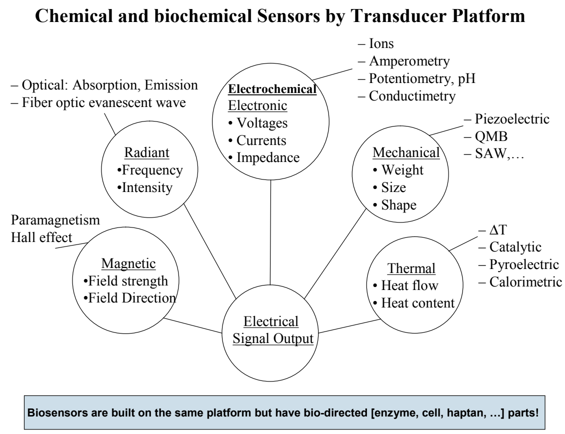

Fig. 1 *Chemical and biochemical sensors by transducer platform.*

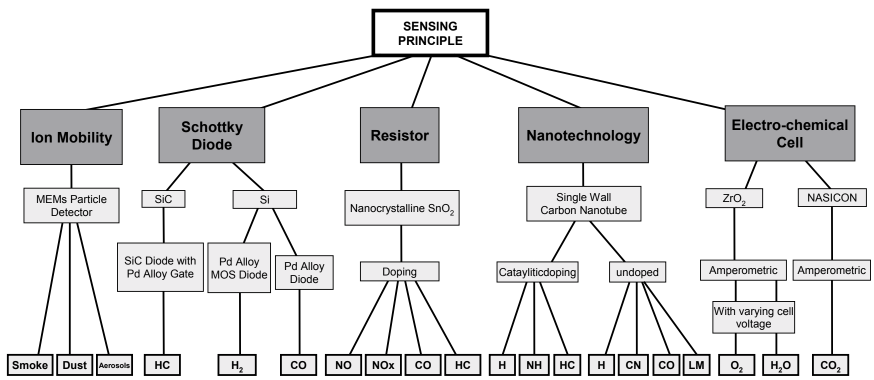

Fig. 2. Electronic and electrochemical gas sensor platform technology. Given a limited number of platforms, a wide range of gases can be detected. Each platform is shown and the target detection species is noted for that configuration of the platform. (Courtesy of Makel Engineering, Inc.[2])

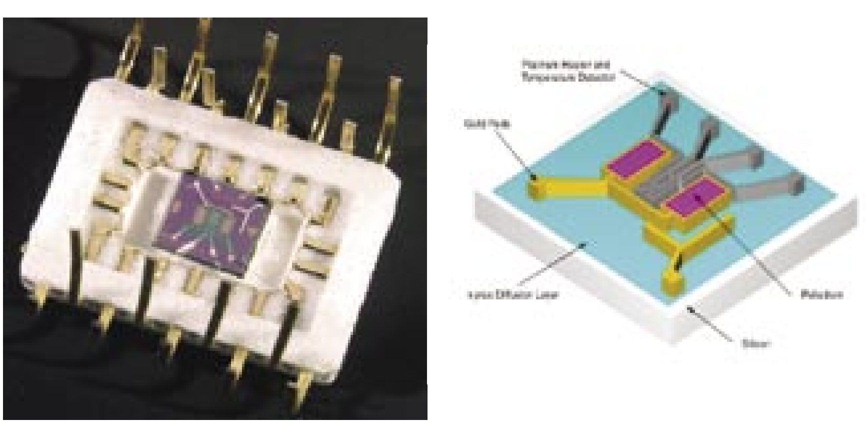

Fig. 3. *Schottky diode based microsensor (hydrogen sensor).*

microfabrication techniques, in addition to miniaturization of chemical analysis systems. These topics are broadly multidisciplinary and, in addition to transductions principles, include areas of chemistry and biochemistry as well as engineering topics such as microfabrication, microfluidics, and signal processing. The following are examples of the types of topics that the ECS Sensor Division explores, ranging from sensor fundamentals to the development and application of complete analytical systems.

One example microsensor is a Schottky diode hydrogen sensor. This sensor is composed of a metal in contact with a semiconductor or a metal in contact with a very thin barrier layer on a semiconductor.[4] The semiconducting properties of the silicon are used for sensor operation. The diode characteristics are such that current can easily flow in one direction and be restricted in another direction. The metal layer serves as a gate for the diode. When a gaseous component selectively absorbs onto the surface of the gate layer, the Schottky energy barrier will change and this change can be measured and correlated with the gas concentration. The diode can be operated in a mode in which the response to changes in gas concentration is exponential.

A Schottky diode based hydrogen gas sensor has been reported.[5,6] The sensor employs a palladium-alloy gate and the sensor is fabricated using silicon-based processing techniques. Figure 3 shows the sensor structure. Hydrogen can be selectively absorbed in a palladium-alloy gate lowering the Schottky energy barrier.[4-7] The change in the diode characteristics can be used to quantify the hydrogen gas presented. A platinum thin film resistance temperature detector (RTD) and heater are integrated into the sensor structure. This permits the sensor to be operated at a controlled elevated temperature enhancing the response time of the sensor.

The Schottky diode platform can be modified to detect a range of gases by altering the gate material or changing the semiconductor to, for example, silicon carbide. Changing the gate alloy can change the viable concentration range of hydrogen detected.[6] Hydrocarbons, which dissociate at higher temperatures, can be detected by replacing the silicon substrate by a high temperature semiconductor like silicon carbide.[7]

Cantilever based sensors show promise for highly sensitive, low power, and compact transducers. The transduction can be based upon either surface stress, which results in bending of the cantilever, or changes in the resonant frequency due to mass changes.[8] Sensitivities as low as 14 ppt have been demonstrated for explosives with selective self-assembled monolayer (SAM) coatings. Arrays of cantilevers could then provide sensitive and broad spectrum sensing platforms for complex mixtures. Arrays of sensors that are responsive to the different analytes can be integrated into a single measurement system. This technology is generally known as machine olfaction or the artificial nose, and an entire ECS proceedings was dedicated to this topic.[9] In the E-nose, sensors with a somewhat less than perfect discrimination between analytes are combined to provide a fingerprint or selective response of the

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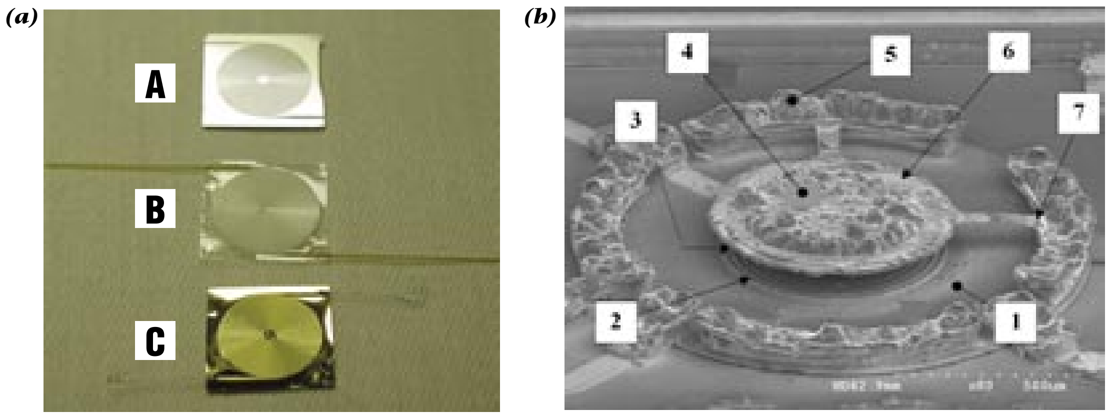

Fig. 4. *(a) (A) silicon mold for fabrication of a miniature GC column, (B) microfabricated 1 m long parylene column, and (C) parylene column with an integrated heater. (b) Scanning electron microscopy (SEM) image of a bistable microvalve, where 1 = Orthonol base; 2 = Au microcoil; 3 = CoMnNiP magnet; 4 = membrane; 5 = circular support; and 6 = soft magnetic dome (Permalloy); 7 = membrane supported legs.*

analyte that can be discriminated above background using pattern recognition methods. This approach is analogous to the biological olfactory system in which each cell receptor responds to a number of analytes and the response pattern is indicative of the odor. Sensor arrays could ultimately lead to artificially intelligent robots that are aware of their surroundings.

A micrototal analytical system, sometimes called the lab-on-a-chip, contains many or all the elements typically found in larger analytical instrumentation including a sampling system with pre-concentration, sample conditioner, separation system, and a detection system. Sensor arrays can be used for characterizing the chemical or biochemical space and the sampler and computer or data processor for data acquisition, data manipulation, and display. Sensor arrays are able to mimic our human sensor systems, *i.e.*, the eye is an optical sensor array, the nose is a chemical gas sensor array, the tongue is a liquid chemical sensor array, the ear is an array of acoustic sensors. Sensor arrays can be homogeneous (made of many of the same kind of sensors) or heterogeneous (made of different or orthogonally responding sensors) and performance is generally better for a heterogeneous array of orthogonal sensors.

The issue of manipulation of the sample and its introduction to a chemical sensor array is often achieved with microfluidics technology. Combining photolithographic processes to define three-dimensional (3D) structures can accomplish the necessary fluid handling, mixing, and separation through chromatography. For example, recent demonstrations of miniature gas chromatography and liquid chromatography with micromachined separation columns illustrates how miniaturization of chemical analytical methods reduces the separation time to a time short enough that one may consider the measurement equivalent to real-time sensing. Low thermal mass gas chromatography (GC) columns, shown in Fig. 4a, require 50 mW to achieve an operation temperature of 100˚C and can be utilized in miniature GC systems.[10]

A microvalve is also an important building block for control in fluidic systems. A microfabricated latching electromechanical valve built on a single substrate is shown in Fig. 4b. The actuator is 1 mm in diameter and comprises a permanent magnet defined on a movable Permalloy membrane, approximately 400 µm in diameter, supported by two cantilever beams. When current is applied to the coil a magnetic field is generated which attracts the membrane, hence closing off the flow channel in the center. Once closed, the permanent magnet is strong enough to maintain the valve in the closed condition without current applied to the coil. This actuator has an efficient magnetic design so that low energy consumption of only 3 mJ is achieved when actuated. The microfabricated integrated design results in arrays of miniature latching microvalves with a low dead-volume, rapid actuation, and low power consumption.[11] Realization of valves on a single substrate has the advantage of integration for bio and chemical analysis systems. The valves do not have to be built on silicon; because the temperature processing is low, a plastic substrate may also be considered.

Biosensors include a biological recognition element, along with a transducer. Examples include those based upon enzymes, antibodies, deoxyribonucleic acid (DNA), or cell membrane receptors. Proteomics is an exciting area and immunoassays can provide medical diagnostics which are suitable for analysis in a microfluidic format. For example, in a sandwich assay where the primary antibody is bound to paramagnetic beads, an effective means for mixing and separation can be achieved. Detection of bound target antigen is then determined with an enzyme-labeled secondary antibody. When an enzymatic substrate is introduced, the quantity of bound complex may be determined by amperometric measurements with microelectrodes, thereby simplifying instrumentation compared to other techniques. A further advantage is that the small sample volume increases the sensitivity of the enzyme labeled immunoassay.[12] Other microfluidic approaches include the use of electrophoretic separation based upon molecular properties. Microfluidics has also been applied to DNA sequencing as well as DNA separation and hybridization and polymerase chain reaction (PCR) on-a-chip. The commercial markets for biomedical applications are large and because they often require disposable sensors, the technology selected must be suitable for low cost making plastic microelectromechanical systems (MEMS) and plastic manufacturing process are attractive.

Microinstrumentation activities have produced sensor-sized miniaturized mass-spectrometers, gas chromatographs, NMR, and, more recently, micro-Raman instruments. The key advantages of miniaturization are more rapid analysis, and hence a higher sample throughput and smaller required sample volumes. However, to date, the miniature systems have done so at the expense of analytical performance and there is much more work to be done to optimize microinstruments.

Given the range of the technologies available, in the end, the application or customer does not really care if there is a sensor in the little sensor box, an array, or a complete analytical system. They care about getting the measurement and information they need. However, the sensing mechanism used is important to developers and in effective application and must be chosen carefully to understand how the overall performance relates to the sensor system. The surface coating on the sensor often defines the specificity, sensitivity, response time, and stability and selective functionalization of the sensor is critical. In miniature analytical instruments, a batch process is used so that there are several ways to obtain improved sensor performance: improved sensitivity of detectors, improved sampling systems, and improved separation or preconcentration of analytes.

What is exciting in sensor research and development today? This is a tough question. There are many significant innovations and inventions being made daily. Micro- and nanotechnology, novel materials, and smaller, smarter, and more effective electronic systems will play an important role in the future of sensors. To fulfill the promise of ubiquitous sensor systems providing situational awareness at low cost, there must be a demonstrated benefit that is only gained through further miniaturization. For example, new nanowire-based materials that have unique sensing properties can provide higher sensitivity, greater selectivity, and possibly improved stability at a lower cost[13] and such improvements are necessary to the sensor future.

Sensors can improve the world through diagnostics in medical applications; improved performance of energy sources like fuel cells and batteries and solar power; improved health and safety and security for people; sensors for exploring space and the known universe; and improved environmental monitoring. The seed technologies are now being developed for a long-term vision that includes intelligent systems that are self-monitoring, self-correcting and repairing, and self-modifying or morphing not unlike sentient beings. The ability for a system to see (photonic technology), feel (physical measurements), smell (electronic noses), hear (ultrasonics), think/communicate (smart electronics and wireless), and move (sensors integrated with actuators), is progressing rapidly and suggests an exciting future for sensors.[14]

Recent symposia held at ECS meetings include: MEMS and sensors, nanosensors, electrochemical sensors, acoustic sensors, cantilever sensors, and electronic noses.[9] In addition, the miniaturization of instruments for chemical analysis (lab-on-a-chip) has become an increasingly active area at ECS meetings. The chemical and biosensors symposium and MEMS symposium are held regularly. The quality of the symposia is directly dependent on the inputs of the scientific and engineering communities; new ideas, visions, and members are actively sought in these fields which can have so much impact on the way people live. ■

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