Chapter 2
Transduction Principles

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Abstract This chapter presents the most common fundamental transduction principles used in microsensors. Each section provides an overview of the theory and then gives an example of a sensor that uses the transduction principle being described. A classification of measurands is presented as well as the most common transduction techniques including piezoresistance, piezoelectricity, capacitive, resistive, tunneling, thermoelectricity, optical and radiation-based techniques, and electrochemical.

Introduction

This chapter presents the most common fundamental transduction principles used in microsensors. Each section provides an overview of the theory and then gives an example of a sensor that uses the transduction principle being described.

Wikipedia defines a transducer as follows.

A transducer is a device, usually electrical, electronic, or electro-mechanical, that converts one type of energy to another for the purpose of measurement or information transfer. Most transducers are either sensors or actuators. In a broader sense, a transducer is sometimes defined as any device that senses or converts a signal from one form to another. (www.Wikipedia.com)

In a similar definition a transducer is defined as a device providing a usable output in response to a specific measurand, where the measurand is defined to be the physical quantity, property, or condition that is to be measured (Norton 1982). It is further stated here that when one is designing a sensor or trying to choose the appropriate transduction technique there are a few questions one can ask, including: What is the measurand? What is the principle of transduction? What is the sensing element? What are the limits of the measurand to which the transducer will need to respond?

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White has presented a classification scheme for measurands or properties one may be interested in measuring. The main categories and significant subcategories are given in Table 2.1 (White 1987).

Transducers are typically designed to sense a specific measurand and to ideally respond only to that particular measurand. In reality a transducer will most likely respond to the measurand in question and will also respond to other energy sources that act on the sensor that are not of interest. These are considered sources of noise, for example, when measuring strain with a piezoresistor the measurand of interest is strain, however, the resistance will also change with temperature.

Table 2.2 shows the most common transducer types used to quantify the major categories of measurand. The sections below provide an overview of the common transduction mechanisms and principles such that one can begin to apply this knowledge to sensor design.

Table 2.1 Classification of Measurands

Measurand	Property of Interest
Acoustic	Wave amplitude, phase, polarization Wave velocity Spectrum
Biological	Identity, concentration, state
Chemical	Identity, concentration, state
Electrical	Current, charge potential, potential difference Field (amplitude, phase, polarization) Conductivity and permittivity
Magnetic	Field (amplitude, phase, polarization) Flux Permeability
Mechanical	Position, velocity, acceleration Force Stress, strain Mass, density Flow Moment, torque Stiffness, compliance Viscosity Crystallinity
Optical and Radiation	Wave amplitude, phase, polarization Spectrum Velocity Energy
Thermal	Temperature Flux Specific heat Thermal conductivity

Table 2.2 Transduction Techniques for Common Measurands

Measurand	Most Common Transduction Techniques Utilized to Quantify the Measurand
Acoustic	Piezoelectric Piezoresistive Capacitive Optical
Biological	Piezoelectric Piezoresistive Electrical Optical
Chemical	Piezoelectric Piezoresistive Electrochemical Electrical Optical
Electrical	Electrical Optical
Magnetic	Piezoresistive Piezoelectric Electrical – capacitive, tunneling, Optical
Mechanical	Piezoelectric Piezoresistive Capacitive Optical
Optical and Radiation	Thermoelectric (Seebeck) Photosensitivity (photovoltaic, photoelectric, photoconductors, photodiodes, and phototransistors)
Thermal	Thermoelectric Photosensitivity Electric – resistive

Piezoresistivity

Piezoresistivity is, in its most basic form, the change in a material's resistance resulting from a change in stress in the material. The word piezo is derived from the Greek word *piezein*, which means to press or squeeze. Many materials exhibit the piezoresistive effect and it is typically quantified by what is termed the gauge factor. The gauge factor is the change in resistance per given strain per starting resistance and can be described via the following equation,

$$GF = \frac{\Delta R}{R.Strain}. \tag{2.1}$$

The gauge factor for silicon decreases with increasing impurity concentrations and this can be predicted by model. Controlled doping is typically accomplished via ion implantation of the specific doping ion into the silicon to define the piezoresistor. An alternative technique is to deposit a film containing the doping ion over a patterned Si surface and then use a temperature treatment to drive the dopant into the depth of the Si.

The piezoresistive gauge factor decreases as temperature increases, and this can also be predicted. The coefficients increase linearly with the inverse of temperature. One can find a deep description of the mathematics in Sze (1994).

When deciding if piezoresistance can be used as a transduction measurand for a particular measurand one only has to determine if the sensor can be designed such that the measurand can produce a stress on a portion of the device where a piezoresistor can be located. Examples of measurands that are quantified via piezoresistance include: pressure, vibration, acceleration, and magnetic field. Once it has been decided that the measurand could be quantified via piezoresistance one must determine if it is the best approach that will meet all the specifications of the application, as described in Chapter 1.

A great example of a transducer that uses the piezoresistive effect is a silicon-based MEMS pressure sensor. Silicon-based pressure sensors have been around since the late 1950s and they are a very mature technology. GE Sensing offers a multitude of Si-based pressure sensors for a variety of applications including blood pressure sensing, tire pressure sensing, industrial process measurement, and so on. An overview of one pressure sensor is presented here that is designed to measure tire pressure (www.GESensing.com).

This sensor is approximately 1 by 1 mm and is an absolute pressure sensor, meaning the reference cavity is a vacuum and, once calibrated, the sensor gives the absolute pressure inside the tire. As with most pressure sensors, the electronic readout technique utilizes a Wheatstone bridge.

The sensor element is a thin silicon membrane with embedded piezoresistors. The piezoresistors are formed via an implantation step and the proper doping level is chosen to provide the highest gauge factor. The piezoresistors are positioned in the areas of the membrane that see the highest strain due to the force of the pressure bending the membrane (Fig. 2.1).

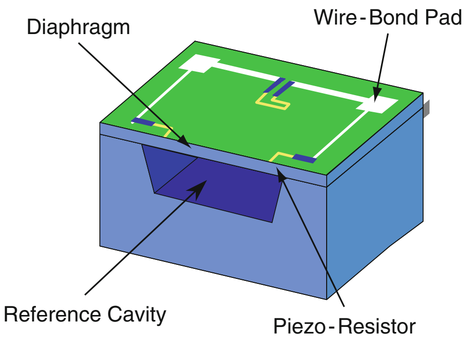

Fig. 2.1 Side view of GE Sensing silicon pressure sensor. (Courtesy of GE Sensing.)

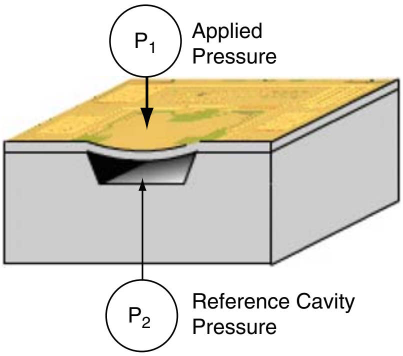

Fig. 2.2 Side view representing diaphragm deflection of GE Sensing silicon pressure sensor. (Courtesy of GE Sensing.)

Many membranes are formed on a silicon wafer using typical microfabrication processes and then this wafer is wafer-bonded in a vacuum environment to a bottom silicon wafer with cavities lined up with the membrane. This forms a drumlike structure with a vacuum cavity lying below a thin membrane. As the external pressure fluctuates, the membrane moves to balance the force between the external pressure and the stretched membrane (Fig. 2.2).

Piezoelectricity

Overview of Theory. Piezoelectricity, as is piezoresistivity, is an electrical effect caused by a change in the strain of a material. In the cause of piezoelectricity, when a piezoelectric material is stressed (compressive or tensile) a charge is induced across the material's faces in response to the magnitude and direction of the strain.

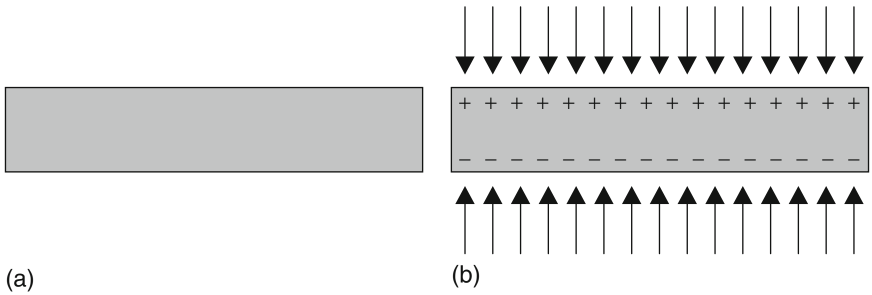

Fig. 2.3 (**a**) Piezoelectric material with no externally applied strain has no net charge on its surfaces. (**b**) The same material under strain produces charges at surface that can be measured

A piezoelectric transducer therefore converts a change in a measurand into a change in electrostatic charge or voltage (Fig. 2.3).

Typical piezoelectric crystal materials include $LiNbO_3$, $LiTaO_3$, $Li_2B_4O_7$, GaAs, and quartz. Typical thin film-based piezoelectric materialso include ZnO, AlN, and PZT ($Pb(Zr, Ti)O_3$). PZT is probably the most widely used piezoelectric material for sensing in applications such as accelerometers, vibrometers, ultrasound, and high dynamic range ac pressure sensing.

In microsensors, piezoelectric materials can be either directly deposited onto the device or they may be integrated into the device, for example, lamination of a piezoelectric polymer film. Because PZT has an order of magnitude higher piezoelectric effect than ZnO and AlN many techniques have been developed to integrate PZT with a microdevice, including sol–gel and sputtering. ZnO and AlN films have also been integrated into microdevices for the purpose of transduction (Royer et al. 1983; Ried et al. 1993; Ko et al. 2003). The definition of methods and measurement of piezoelectric crystal units is reported in detail in Halfner (1969).

An example microdevice utilizing a piezoelectric transduction technique was recently presented at the 2006 Transducers Conference at Hilton Head (Horowitz et al. 2006). The device presented was a micromachined piezoelectric microphone for aeroacoustics applications. Although there had been previous research done on MEMS-based microphones most of them have been developed for audio applications. The microphone reported at 2006 Hilton Head was designed for high sound pressure applications in excess of 160 dB with a bandwidth of >50 kHz.

The microphone was fabricated by combining a sol–gel PZT (lead zirconate–titanate) deposition process on a silicon-on-insulator wafer. The PZT was deposited onto a 1.80 mm diameter 3 μm thick Si diaphragm. The PZT was processed and lithographically defined to an annular ring near the diaphragm edge to maximize the sensitivity. The PZT layer was 270 nm thick and was placed between two thin metal electrodes. A diffusion barrier separated the PZT from the silicon diaphragm. As acoustic energy impinged upon the diaphragm it moved. As it moved, the piezoelectric material experienced stress in the *z*-axis and the charge at its surfaces changed in response to this stress and this charge was measured.

Test results for the microphone showed a sensitivity of 0.75 uV/Pa with a linear dynamic range from 47.8 to 169 dB and a resonant frequency of 50.8 kHz.

Electrical—Resistance, Capacitance, Impedance, Tunneling

There are many ways to convert a change in an external measurand into a change in an electrical signal directly, particularly in a MEMS device, where there are moving parts that can be accessed electrically or integrated thin films that often have electrical properties based on the environment to which they are exposed.

Resistance: One key transduction technique that converts the measurand to a change in resistance is piezoresistance, which, because of its widespread use in microdevices was covered separately above. Other resistance-based transduction techniques also rely on the measurand interacting with a film or bulk structure and hence changing an electrical property. For example, certain polymers have a moisture- or gas-sensitive resistivity. Another example is in the measurement of temperature, where because resistance of a material is a function of temperature it can be directly used to measure temperature; this type of device is referred to as a thermistor.

An example of a device that uses a materials change in resistance due to exposure to the measurand can be seen in the work of Valentini et al. (2004). This device uses carbon nanotubes (CNTs) as the functional transducer material. Carbon nanotubes present extremely high surface-to-volume ratios and have recently seen significant attention for their gas adsorption properties (Treacy 1996). Valentini et al. used an interdigital electrode structure made from platinum deposited and patterned on top of a silicon nitride film. The CNTs were then grown from a catalyst between the Pt electrodes to heights of approximately 200 nm. The results showed that the resistance of the film on CNTs decreased when in contact with NO_2 and increased when in contact with NH_3, ethanol, water vapor, and C_6H_6. The detection limit for NO_2 was shown to be as low at 10 ppb.

Capacitance: In this transduction technique the measurand interacts with the device to change the capacitance value of a capacitor. This change can be induced by changing the effective distance between the two plates or electrodes of the capacitor or by changing the dielectric constant of the insulator material. Examples of both are given below.

The capacitive transduction technique that can be used to measure pressure is capacitance. In a typical silicon-based capacitive pressure sensor the design is similar to a piezoresistive pressure sensor as described above. Instead of implanting piezoresistors into the diaphragm, the diaphragm itself is used as one plate of a capacitor. Alternatively a metal layer can be placed on or embedded in the diaphragm. The second plate or electrode is located at the bottom of the gap (see Fig. 2.5). In the sensor shown in Fig. 2.4 the substrate is a degenerately doped silicon wafer and the membrane has been wafer-bonded under vacuum to a patterned oxide layer. Contact is made to the substrate through an opening in the oxide and directly to the also

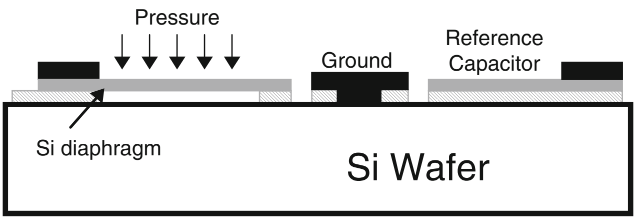

Fig. 2.4 Capacitive-based pressure sensor

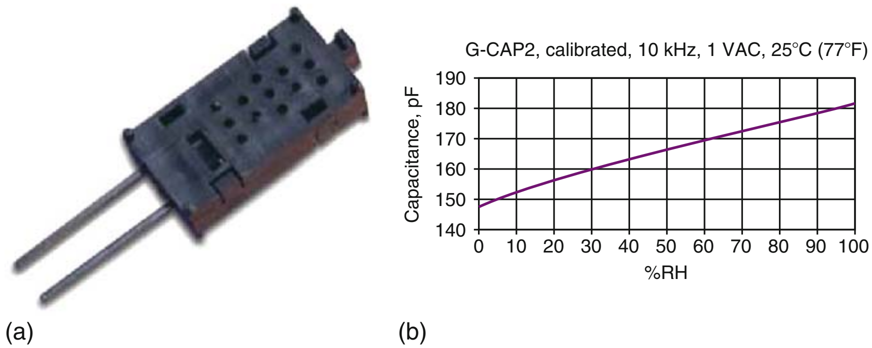

Fig. 2.5 (**a**) G-CAP2™ Humidity Sensor; (**b**) response curve for G-CAP2™ capacitive humidity sensor. (Courtesy of GE Sensing.)

degenerately doped silicon membrane. A capacitor with an oxide dielectric as a reference is placed next to the sensor.

As the external pressure changes the diaphragm moves and the distance between the diaphragm and the lower electrode changes, thus changing the capacitance of the device. One advantage of a capacitive-based pressure sensor over a piezoresistive approach is the lower power consumption of the sensor itself. Another advantage is the capacitive approach tends to have higher sensitivity if properly designed (Eaton and Smith 1997).

The G-Cap Moisture Sensor offered by GE Sensing is an example of a device that utilizes the change in capacitance of a thin film in response to the measurand. In this case the functional material is thin polymeric film sandwiched between two thin patterned electrodes. The polymeric film was developed to allow for measurement of a wide range of relative humidity from 0 to 100% and it can survive total immersion in water without loss of accuracy. The typical capacitance of the sensor is in the range of 140–190 pF and it changes linearly with %RH. The capacitance is measured between 1 kHz and 1 MHz (Fig. 2.5). The sensitivity to changes of temperature can be calibrated and is typically less than 0.05% RH/°F.

Impedance: This is very similar in nature to the resistance or capacitance technique. In impedance-based transduction the AC impedance of a component of the device is measured and monitored. Often there is a material that is used to measure an environmental parameter, such as humidity or local magnetic field.

One impedance-based transduction method that has received a lot of attention in recent years is giant magneto impedance (GMI). This effect refers to a material's very large change in resistance due to an applied magnetic field. This effect has been seen in amorphous wire, ribbons, and thin films. An analogous effect is called giant stress impedance (GSI), where a change in stress causes a large change in impedance. The GMI effect is seen in many high-permeability materials such as amorphous soft magnetic wires with Fe-based or Co-based compositions (Zribi et al. 2005; Han et al. 2005; Garcia et al. 2005). This effect depends on the material's permeability which is a function of many factors including domain configurations, material geometry, anisotropy, and excitation frequency. The GMI effect can be expressed as an impedance ratio given by Equation (2.2),

$$\Delta Z / Z = [Z(H) - Z(H\max)] / Z(H\max), \tag{2.2}$$

where Z is the impedance, ΔZ is the change in impedance, H is the magnetic field applied to the sensor, and H_{max} is the max field. GSI can be expressed in a similar fashion where the magnetic field is replaced with stress.

Han et al. (2005) provide a nice overview of sensors utilizing the GMI and GSI effect. The applications of these sensors include magnetic field measurement, a position measurement for the location of a catheter in the human body, nondestructive testing, and electronic surveillance. Zribi et al. (2005) also present an oil-free stress impedance pressure sensor for harsh environments.

Tunneling: Another interesting technique employed in micro- and nanosystems for transduction of a measurand value into an electrical signal is electrical tunneling. Typically what is done in this case is a mechanical component becomes one electrode in a two-electrode circuit. This mechanical component will have a tip or surface placed within a few to tens of nanometers from the second stationary electrode. The mechanical component with the tip will move in response to the measurand. As it moves, the distance between the tip and the stationary electrode will change and hence the tunneling current will change. This technique can be used to measure very tiny changes in the measurand if properly designed.

A number of publications have addressed the design, fabrication, and performance of tunneling-based sensors. Liu and Kenny (2001) have demonstrated a MEMS-based high-precision, wide-bandwidth micromachined tunneling accelerometer with a resolution of 20 ng/sqrt Hz and 5 Hz–1.5 kHz bandwidth. The design consists of a cantilever tip substrate, a proof mass, substrate, and a cap substrate all wafer-bonded together. The accelerometer is operated at a pressure of 10 mTorr to reduce thermomechanical noise and increase Q to above 100. A feedback controller is used to maintain the tunneling gap at 10 Å.

Thermoelectricity

Overview of Theory

Thermoelectricity: This transduction technique converts the value of the measurand into a voltage (or electromotive force) generated by the potential difference between the junctions of two selected dissimilar materials due to the Seebeck effect. The Seebeck effect is well known and is the technology employed in thermocouples, where, as the temperature of the junction changes, the voltage across the junction changes. Thus, a thermocouple works by measuring the difference in potential caused by the dissimilar wires. Several thermocouples in series are called a thermopile. This technique is also used in silicon-based devices to measure temperature using a noncontact approach. The Seebeck effect can be described by Equation (2.3) referring to Fig. 2.6:

$$V = (S_B - S_A) / (T_2 - T_1), \tag{2.3}$$

where S_A and S_B are the Seebeck coefficients of materials *A* and *B*, respectively and T_1 and T_2 are the temperatures of the two junctions.

A good example of a microsensor utilizing the Seebeck effect for transduction is the GE silicon-based IR thermopile (www.GESensing.com). The IR thermopile sensor consists of a number (about 40) of thermocouple pairs connected in series and covered with a high emissivity coating. The hot junctions are thermally isolated from the cold junctions and are exposed to the incident IR radiation. The cold junctions are attached to a heat sink. GE's device is built on a silicon wafer and the thermocouple radiation detection junctions are placed on a thin, low thermal mass diaphragm, and the reference junctions are placed off the membrane on the thick silicon wafer (Figs. 2.7 and 2.8). A thermistor is placed in the finished package as a reference.

The IR thermopile device allows for measurement of temperature without direct contact with fast, millisecond response times due to the low thermal mass of the diaphragm. Applications include tympanic thermometers for body temperature measurement, food temperature measurement in microwave ovens, measuring temperatures inside vehicles, and many others.

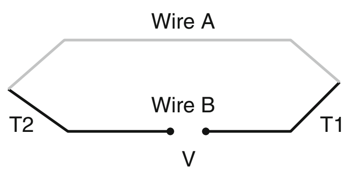

Fig. 2.6 Thermocouple consisting of wire of material A connected to wire of material B

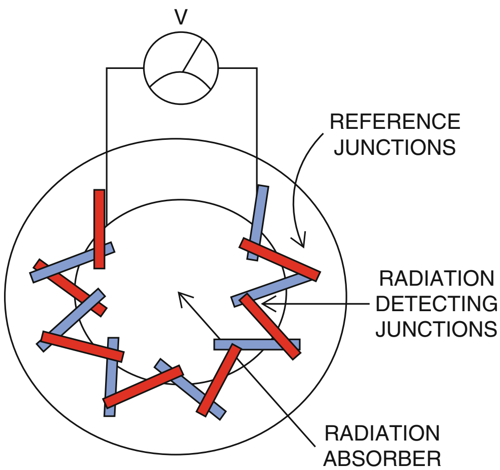

Fig. 2.7 Arrangement of thermocouple junctions on the silicon IR sensor

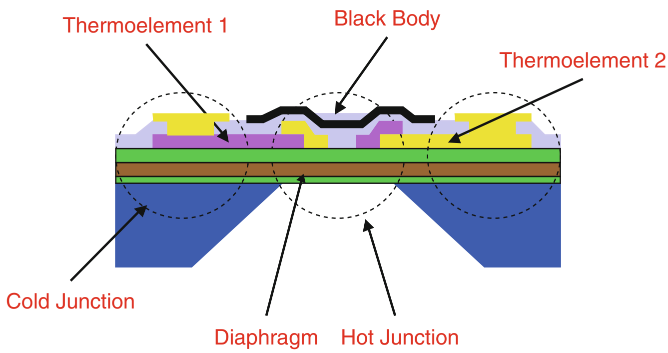

Fig. 2.8 Cross-section of the GE thermopile IR sensing chip. (Courtesy of GE Sensing, www.GESensing.com.)

Optical and Radiation Techniques

Overview of Theory

Optical techniques can be used to measure the change in a mechanical measurand, or quantify an optical spectrum for chemical or biological analysis using IR, UV, or other radiation. The optical sensing techniques typically probe the material/object to be sensed directly or indirectly via some structure. In all optical techniques a detector must quantify the optical signal. Typically some property of the optical beam returning from the sample is compared to the source beam, including amplitude and phase information. A radiation-sensitive detector can be used either combined with a radiative probe (e.g., Raman spectroscopy) or to measure directly a radiative property of the sample/source being measured (e.g., gamma detection).

Electromagnetic or radiant energy is carried by photons spanning wavelengths of cosmic rays from 10^{-9} um to radio waves of 10^{14} um long. Electromagnetic radiation primarily interacts with semiconductors via absorption processes and interference, diffraction, reflection, polarization, transmission, and refraction all play a role (Sze 1994). In the measurement of radiation there are many different transduction techniques that can be used including photovoltaic, photoelectric, photoconductors, photodiodes, and phototransistors.

In a photovoltaic or photodiode light is incident upon a junction between dissimilar materials and a voltage is generated. This technique can be used to measure the intensity of a light source and is also used in power generation. In photoconduction a change in measurand is converted to a change in the resistance or conductance of a semiconductor material due to a change in the amount of illumination incident upon the material. The resistance or conductance can then be measured electronically. In the photoelectric effect an incident photon causes the emission of an electron. A common detector for optical imaging or sensing is the charge-coupled device (CCD).

There is a variety of different sensors that utilize optical or radiation techniques to quantify a measurand. One example is a fiber optic strain sensor, which utilizes a fiber optic with embedded Bragg gratings. The distance between the Bragg gratings changes as the fiber is put under stress or strain and this distance can be measured as an optical beam. This fiber technique is available for temperature and strain and one fiber can have multiple sense locations allowing for multiplexing multiple measurements.

One interesting example of optical sensing where functional nanostructures play a role is surface-enhanced Raman spectroscopy (SERS). In this technique the Raman signal generated from a sample can be greatly enhanced (10^6–10^8) if the sample is in close proximity (nm range) to an appropriately roughened surface (Moskovits 2005). This technique has been used for biosensing applications via using nanoparticles as the SERS substrate and selectively attaching pathogens to the nanoparticles using an antibody approach (Stuart et al. 2005).

Electrochemical

Overview of Theory

There are many variations of approaches to utilizing electrochemistry to make measurements and transducer signals using microsensor technology. The classifications of electrochemical microsensors include: potentiometeric (measurement of potential) and amperometeric (measurement of current). The devices utilized are typically one of the following: chemoresistor, chemocapacitor, chemodiode, chemotransistor, or CHEMFET (Gardner 1994).

This transduction technique can be used to measure or quantify materials in the gas or liquid phase, and includes chemical and biological measurands such as sodium ion concentration, oxygen concentration, and glucose measurement. The underlying principle is to utilize an electrochemical reaction between the species of interest and the functional material on the device and to measure the degree of that interaction via the measurement of an electrical property of the active layer in the device or the direct electrical signal that is produced from the reaction.

Gardner gives a good overview of the measurement of chemical and biological sensing using the electrochemical approach (Gardner 1994).

The potentiometric technique is described here to give a better understanding of electrochemical transduction. In this technique the potential difference between an indicator or reference electrode and the sample electrode is measured. This approach is prevalent in macroscopic systems today and scales well to microsensors because the magnitude of the potential does not change with the size of the electrode. The typical implementation of a potentiometric microsensor is via a CHEMFET. In a CHEMFET the gate of a field effect transistor (FET) can be chemically modulated and gives rise to three types of microsensors: the ion-sensitive FET (ISFET), the work function FET, and the enzymatically selective FET (ENFET) (Janata 2003).

ISFETS are well adapted to the measurement of ions in aqueous solutions and often utilize polymer-based ion sensitive layers such as polyvinlychloride, poly-HEMS/siloprene, polyurethane/acrylate, and polysiloxane (Humenyuk et al. 2006). Humenyuk et al. recently published on the development of pNH_4-ISFETS for water analysis using a polysiloxane-based ion selective layer. The device was fabricated on *N*-type silicon using standard *P*-well technology. The gate structure was a LPCVD deposited 80 nm Si_3N_4 layer with a polysiloxane copolymer deposited on top. A reference metal oxide/nitride FET was fabricated on each die for drift and temperature compensation. Sensitivity was shown to be around 47 mV/pNH_4 through the concentration range of 1–5 pNH_4.

Summary

Fundamentally transduction is taking energy from one form and transferring it into another and quantifying that energy change or energy input. As one can see there are a number of measurands that can be quantified via a variety of transduction techniques. There are often multiple transduction approaches to quantify a measurand and one must fully understand the specifications of the application in order to down-select approaches. The final approach may not necessarily be clear and experimentation or innovation may be required to determine or define the best approach.

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