3

Silicon Sensors: An Introduction

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3.1 Introduction

In the last 30 years, silicon sensors have been able to benefit from huge price/performance improvements in the IC industry. One of the problems facing sensors compared with standard ICs is that the volume is often smaller. Although millions of pressure sensors are produced each year, they are designed for numerous applications that have many pressure ranges. Despite these problems, silicon sensors are now finding a growing market leading to reduced unit costs.

Sensors form only one part of the total system and it is essential that all components function correctly to have a useful system. Figure 3.1 shows these components. On the left-hand side is the input transducer, or sensor. The signal is often not in a desired form and can also contain cross-sensitivities. The modifier needs to convert this signal into the required form and, where possible, remove unwanted effects such as cross-sensitivity. Once the desired format is obtained the signal can be transmitted to the outside world using the output transducer (display, actuator, storage or transmission).

3.2 Measurement and Control Systems

The name 'information-processing system' stands for a wide spectrum of systems which comprise computers, oscilloscopes, door locks, clinical thermometers, satellites, word processors, cash registers, automatic vending machines, slide projectors, etc. All these systems process information in one way or another. In this text we will concentrate on a subgroup of information processing systems, namely modern electronic measurement and control systems, and above all, attention will be focused on the transducers or sensors used in these systems.

In the input transducer, which these days is called the sensor, measures of such physical or chemical quantities as light intensity, displacement, temperature, magnetic field or pH value are converted into an electrical or electronic signal. For this purpose a huge number of

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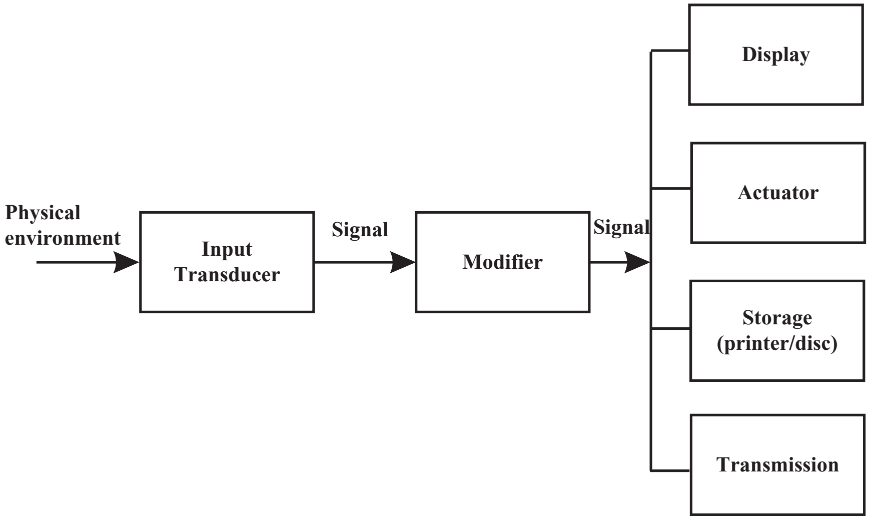


Figure 3.1 Block diagram of an information-processing system

physical and chemical effects are already available. An input transducer is distinguished by the fact that the energy carrying the signal is converted from nonelectrical into electrical form. In the second block, the modifier, the electronic signal is, as the name implies, modified. The modifier can be as simple as an amplifier, but it can also consist of a microprocessor or even of the central processing unit of a large-scale computer. In contrast to transducers, in a modifier the form of the energy carrying the signal is not converted into another form. In a modifier analog-to-digital or current-to-frequency conversion can occur, in which case the signal can be amplified or filtered or, when the modifier consists of a computer, the signal can be subjected to an extended algorithm. However, the signal is always carried by electrical energy at the input as well as at the output of the modifier. The advances made in integrated circuit technology have made it possible to produce very sophisticated modifiers with an unprecedentedly low price/performance ratio. For instance, microprocessors, memory chips and operational amplifiers are currently available at moderate costs with most prices still continuing to decrease while versatility and reliability continue to increase.

Lastly, in the output transducer the electrical signal is again converted into a nonelectrical signal which can be detected by at least one of the five human senses. For example, in a display the signal is carried by radiant energy and in a loudspeaker by mechanical (acoustic) energy.

When the instrument is used for control purposes, the output signal is often mechanical. When a feedback loop is introduced between the output of the output transducer and the system generating the physical quantity to be measured, the physical quantity can be controlled to be at a desired level determined beforehand.

When registration or storage of the information is envisaged, a recording head or a thermal printing head can be used as the output transducer. Finally, an output transducer may be necessary for the transmission of information. When electromagnetic radiation is used as a signal carrier, the output transducer is in the form of a simple antenna. The similarity between display devices and transmission devices is striking. In an optical display, the visible electromagnetic radiation carries the information to the eye of the human observer. Therefore, a display device is in fact also a transmission device. In order not to add to the confusion surrounding the terminology in the instrumentation field, the term 'display device' will be used in this book whenever a transmission device is meant where a human observer is the receiver of the information. In all other cases we refer to a 'transmission device'.

The above observations also apply to registration devices. For example, a printing head transfers information onto paper. A human observer can make immediate use of this on-line output, in which case the printer acts as a display device. When the information is printed, in order to store it for later use, the printer acts as a storage device.

To avoid confusion, we will not use the term 'display device' in any case where material is employed for storage.

3.3 Transducers

3.3.1 Form of Signal-carrying Energy

As shown in the preceding section, an instrumentation system consists of two blocks, the transducers, in which the form of the signal-carrying energy is converted into another form, and one block, the modifier, in which the form does not change. In order to obtain insight into the different signal conversions in transducers, it is useful to consider the various forms in which energy manifests itself and to study the physical effects by means of which energy conversion can take place. From a physical point of view, as most textbooks on physics elucidate, we can distinguish the following forms of energy:

(1) Electromagnetic radiant energy: this energy is related to electromagnetic radiowaves, microwaves, infrared, visible light, ultraviolet, X-rays and gamma-rays.
(2) Gravitational energy: this energy concerns the gravitational attraction between a mass and the earth.
(3) Mechanical energy: this energy pertains to mechanical forces, displacements, flows, etc.
(4) Thermal energy: this energy is related to the kinetic energy of atoms and molecules.
(5) Electrostatic and electromagnetic energy: this energy concerns electric and magnetic fields, currents and voltages.
(6) Molecular energy: this energy is the bond energy which holds atoms together in a molecule.
(7) Atomic energy: this energy is the binding energy which is related to the forces between nucleus and electrons.
(8) Nuclear energy: this energy is the binding energy which holds the nuclei together.
(9) Mass energy: this energy is proposed and described by Einstein as part of his relativity theory.

In today's search for alternative energy sources, studies are focused on all methods that allow the efficient conversion from one of the nonelectrical energy forms into the electrical energy form.

In order to characterize the transducers in the instrument field, it is not necessary to consider all of the above-mentioned energy forms. Although, with some imagination, one can envisage information transport which makes use of nuclear or mass energy, for practical purposes the energy forms are grouped into only six main energy domains, which in turn lead to six main signal domains.

Gravitational and mechanical energy are brought together in the mechanical signal domain. Electromagnetic waves are considered radiant energy. Molecular energy and atomic energy are brought together in what is called the chemical signal domain. Nuclear and mass energy are not considered here, for obvious reasons.

We now have the six signal domains [1]:

- radiant signal domain;
- mechanical signal domain;
- thermal signal domain;
- electrical signal domain;
- magnetic signal domain;
- chemical signal domain.

Based on this division, all measurement and control systems can be represented by the block diagram in Figure 3.2 [2].

In the input transducer and the output transducer, the form of the signal carrier is converted, whereas in the modifier the form remains the same. Today electrical energy is preferred as a signal carrier above all other forms of energy. Electrical energy has been shown to be very versatile, which is a fact reinforced by the availability of sophisticated, low-cost microelectronic components. To illustrate this, an electronic thermometer is indicated in Figure 3.2. In the input transducer thermal energy is converted into electrical energy by means of, for instance, the Seebeck effect. In the modifier the small electronic signal is modified, or amplified, and the signal is converted from analog to digital. In the output transducer the digital signal is converted into a radiant (optical) signal, for instance, by means of a liquid-crystal display. The optical signal makes it possible to visually read the temperature. Though electrical energy is very much the preferred signal carrier for the modifier, other energy forms are still being used in many applications. Mechanical energy is still being used as a signal carrier in mercury thermometers, in the barometer, in many inclinometers, in many speedometers, in standard typewriters, in scales and in many other instruments. Such devices can be produced at very low cost and are often very reliable. Therefore, it is to be expected that these devices will remain on the market for years to come. However, when such devices are applied in

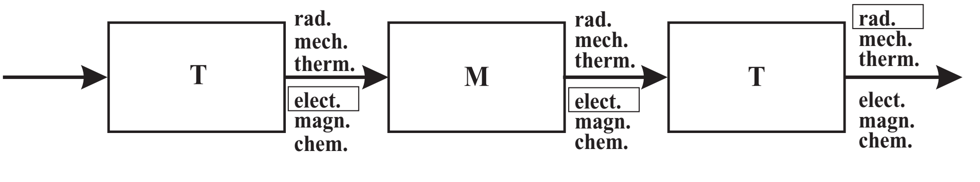


Figure 3.2 General block diagram of an instrumentation system indicating the six different forms of signal-carrying energies. An electronic thermometer is indicated by rectangles

control systems, which require signal transmission over long distances, mechanical energy has proven to be a rather inconvenient signal carrier. For such purposes, electrical or electronic devices such as thermostats for central heating systems, piezoresistive pressure sensors for the processing industry, and load sensors for automatic filling machines, were introduced many years ago.

3.3.2 Signal Conversion in Transducers

In the input transducer a nonelectrical signal is converted into an electrical signal. As has just been discussed, there are six signal domains, which include the electrical signal domain. Because the carrier form is converted in a transducer, one of five nonelectrical signals is converted into an electrical signal in an input transducer.

This statement is subject to some dispute, because there are also input transducers that detect electrical signals such as a current or an electric field. However, if we do not regard electrical signals as input measurands, a large group of important input transducers would not be discussed. A solution to this problem would be to define a transducer as a device in which a signal from one of the six signal domains, including electrical signals, is converted into an electronic signal. However, careful consideration of this suggestion shows that it tends to generate more confusion than insight. In fact, this uncertainty about a proper definition is related to a wider problem.

If one considers these different possibilities, the physics-oriented approach offers a convenient description of the transducer field. Table 3.1 gives the six signal domains with the most important physical parameters. Electrical parameters usually represent a signal from one of the nonelectrical signal domains. Examples are given in Table 3.1.

When electrical parameters such as current or voltage have to be measured, using transducers is not necessary. The entire electronic instrumentation field is made up of instruments consisting of only a modifier and a display unit; therefore, they will not be considered here.

Looking at the physical parameter-oriented approach, the input transducer field can be depicted by the diagram in Figure 3.3 [3]. Each sphere represents a signal domain and in each transducer a one-step conversion occurs in the direction of the electrical signal domain, which is indicated by an arrow. By employing the Seebeck effect, for instance, a transducer can be constructed which converts a temperature difference into an electrical signal. It is also possible to employ the piezoelectric effect to convert a mechanical signal into an electrical signal.

Table 3.1 The six signal domains

Radiant signals	Light intensity, wavelength, polarization, phase, reflectance, transmittance
Mechanical signals	Force, pressure, torque, vacuum, flow, volume, thickness, mass, level, position, displacement velocity, acceleration, tilt, roughness, acoustic wavelength and amplitude
Thermal signals	Temperature, heat, specific heat, entropy, heat flow
Electrical signals	Voltage, current, charge, resistance, inductance, capacitance, dielectric constant, electric polarization, frequency, pulse duration
Magnetic signals	Field intensity, flux density, moment, magnetization permeability
Chemical signals	Composition, concentration, reaction rate, toxicity, oxidation–reduction potential, pH.

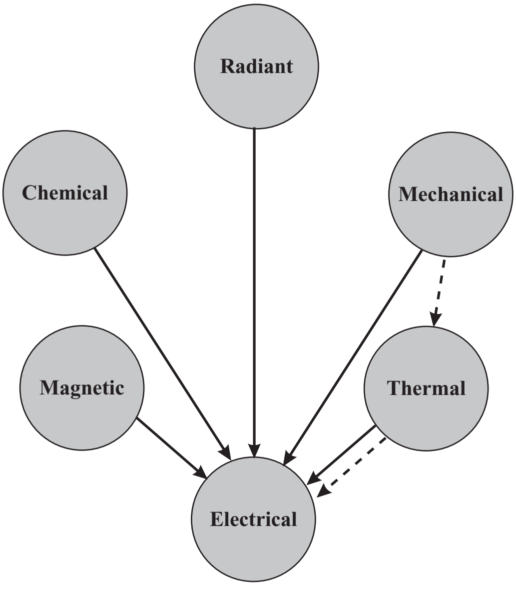


Figure 3.3 Diagram indicating the five possible signal conversions in input transducers. A tandem transducer is indicated by dashed arrows

Many transducers can be based on the use of single effects such as the Seebeck effect or the piezoelectric effect. However, in studying the transducer field, one also frequently encounters transducers in which not one, but two or more single effects are used. For instance, in a certain flow transducer the mechanical measurand or flow is at first converted into a temperature difference which is in turn converted into an electrical signal. In the diagram in Figure 3.3 these conversions are indicated by the dashed arrows. First a mechanical signal is converted into a thermal one and then the thermal signal is converted into the electrical signal. In such a transducer two effects are apparently used in tandem so that from now on we will call such transducers 'tandem transducers'.

A large number of existing physical and chemical effects can be used for signal conversion in transducers.

3.3.3 Smart Silicon Sensors

The measurement and control application field contains a myriad of different transducers, which have been described in many handbooks. Each application field makes use, not unexpectedly, of its own terminology. Transducers represent a very interesting field of research because they encompass large areas of physics and chemistry as well as electrical engineering. Scientists working in these fields, therefore, also contributed their own terminology to the transducer field. It is no wonder that scientists and engineers currently working in this field easily lose sight of the overall picture. Therefore, the aim of this section is to present some consistent terminology based on an analysis of the signal-converting processes.

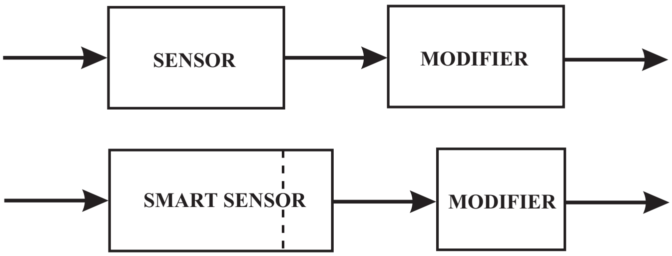


Figure 3.4 By combining sensor and signal-processing circuits a 'smart sensor' is obtained

As in transducers, signal forms are only converted between differing signal domains; the term transducer can be used for both the input and the output of an instrumentation system. To distinguish further between the transducers, the terms 'input transducer' and 'output transducer' are used. However, even though 'transducer' is a good descriptive term in most application fields today, other expressions are in use as well. For instance, in the field of automotive applications the term 'sensor' [4] is much more common than the term 'input transducer'.

The availability of microelectronic components with a very favorable performance/price ratio, gives impetus to the tendency to use electrical energy as the main signal-carrying energy form. In the input transducer, a conversion takes place from one of the nonelectrical energy forms to the electrical energy form. To distinguish such transducers from the general transducer field, we prefer to use the term 'sensor' for transducers that convert toward the electrical signal domain.

In an electronic measurement system the modifier consists of electronic circuits. In order to improve the characteristics of a sensor it is possible to combine a sensor and a part of the signal-processing circuits. In other words, the interface between sensor and modifier is shifted toward the modifier (Figure 3.4)

Such a sensor is known in the literature as an 'intelligent transducer' or a 'smart sensor'. Based on the above discussion of the terminology, it should be clear that the latter term is preferred here, though the adjective 'smart' perhaps promises more than the sensor can deliver. The central unit of the information processing system usually causes less confusion.

In speaking generally about information processing, the term 'modification unit' was used in a preceding section. When discussing measurement or control systems the term 'modifier' is now quite current. When using electrical energy as a signal carrier the term 'signal processor' is also often encountered.

Problems again arise when the use of other expressions for the output transducer is attempted. A signal is converted in the output transducer in such a way that it becomes perceptible to our senses or that it indicates some physical action such as the closing of a valve or the starting of a heater. When a radiant, or more specifically, an optical signal in the visible part of the spectrum is generated by the output transducer, the term 'display' is usually employed. Here the confusion is also considerable. Some other terms used in the literature are, for instance, data presentation element, indicating instrument, readout device, indicator or digital readout. Our confusion is increased when we realize that there are other ways to make signals perceptible to human beings. For instance, the signal can also be converted into the mechanical domain, for example, by using the acoustical domain. A loudspeaker makes

Table 3.2 Signal forms and human senses

Signal domain	Human senses
Radiant	Sight, touch
Mechanical	Hearing, touch, balance
Thermal	Touch
Magnetic	—
Chemical	Smell, taste

the signal perceptible to our sense of hearing. One can even conceive of converting the signal in such a way that we could even touch, smell or taste it. Table 3.2 shows the relationship between the five signal domains and the most important human senses.

It might be useful, if we wish to employ another term besides the general term ‘output transducer’, to use the term ‘display’ in a more general way to refer to all the transducers that convert signal-carrying energy into an energy form which can be perceived by one of our senses. A loudspeaker, then, is an acoustical display. Similarly, visually handicapped individuals might use a touch display for reading information.

An output transducer is used not only to present information but can also change the environment. When an action belonging to the mechanical domain is initiated the term ‘actuator’ is the most frequently used term, although ‘actuation device’ or ‘actor’ is sometimes used.

However, these terms are not used for an output transducer in which an electrical signal is converted into, for instance, a radiant signal for the purpose of heating an object or drilling a hole in a plate of steel. Solid-state or gas lasers can be used to cause such an action and we would certainly not name these output transducers ‘displays’, because the radiant energy is not intended to display any information, but as a form of actuator. The same applies to an output transducer consisting of a piezoelectric ceramic that generates ultrasonic energy not for display purposes but for, say, cleaning watch parts. In view of the above examples, we propose to use the term ‘actuator’ in a more general way and to name all output transducers that initiate some action ‘actuators’. In Table 3.3 some examples of generalized actuators are presented.

Devices that print on material such as paper are in fact actuators. However, if we consider the actuator and the paper as belonging to the same black box, this box would be a display device with material as a signal carrier instead of energy. However, as this view would again generate confusion, we will solely consider energy as a signal carrier, thus rendering the thermal printing head as the actuator in which electrical energy is converted into thermal energy.

Table 3.3 Generalized actuators

Signal domain	Actuator	Action
Radiant	Injection laser	Emission of light
Mechanical	Piezoelectric crystal	Generation of ultrasound
Thermal	Thermal printing head	Melt ink
Magnetic	Recording head	Magnetize medium
Chemical	Battery	Chemical reaction

3.3.4 Self-generating and Modulating Transducers

As shown in Chapter 1, when considering the different transducers and the effects employed, we have seen that some effects can be used to construct transducers that do not require auxiliary energy sources for the signal conversion, while others only yield useful transducers when energy in some form is supplied [5]. The first group of transducers is referred to as ‘self-generating transducers’. These transducers require no source of power other than the signal being measured; examples of this category are solar cells based on the photovoltaic effect and thermocouples based on the Seebeck effect. The second group of transducers is called ‘modulating transducers’. In such transducers an energy flow supplied by an energy source is modulated by the measurand; examples of this category are pressure cells based on the piezoresistive effect and photodetectors based on the photoelectric effect. Self-generating transducers are also often known as ‘active’ transducers, whereas modulating transducers are called ‘passive’ transducers.

3.4 Transducer Technologies

3.4.1 Introduction

As discussed in the preceding sections the introduction of microelectronics into new markets is being seriously hampered by the lack of efficient, low-cost transducers. Until recently much of the research and development work in industry was focused on the electronic modifier so that today, thanks to silicon planar technology, we have at our disposal a huge number of very sophisticated LSI and VLSI components. Because of the impressive high performance/price ratio of these components and the remarkable additional value which microelectronics can lend to almost any product, attempts are currently being made all over the world to apply microelectronics appropriately to innovative products and services. However, these attempts hardly ever lead to instant success, because sufficient numbers of transducers with comparable performance/price ratios do not exist.

Only in those markets where the transducers are simple to construct and inexpensive could microelectronics be introduced on a large scale. The push buttons of a calculator or a computer, the quartz crystal of a watch, the light sensor of a burglar alarm, the mouse of a home computer are, in fact, simple low-cost input transducers. The liquid-crystal display, the TV monitor and light-emitting diodes are low-cost output transducers. For many decades work on transducers has been performed in a huge number of small speciality industries and in the R & D laboratories of the large multinational companies. This has led to an immense number of measuring principles and devices. Books describing this field are often of encyclopaedic dimensions. However, there is still a great need for better low-priced sensors. This demand, caused by the introduction of microelectronics, has now created an avid and renewed interest in the subject. The whole transducer field with respect to technology can be represented as is shown in Figure 3.5

As well as many types of macroscopic principles such as mercury thermometers, bourdon pressure gauges, pneumatic controllers, and linear variable differential transformers for displacement measurement, etc., the entire field also contains the important group of the solid-state transducers.

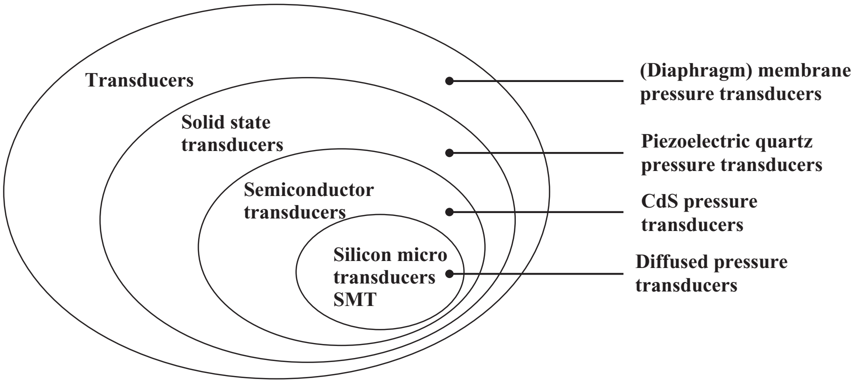


Figure 3.5 Transducers and technology

The operation of these transducers is based upon phenomena that occur in the solid state. The group of solid-state transducers contains, in addition to such devices as piezoelectric quartz pressure transducers, platinum resistance thermometers, LiCl moisture sensors etc., the interesting subgroup of semiconductor transducers. The functioning of these transducers is related to the occurrence of a forbidden energy gap for charge carriers and a filled valence band in semiconducting materials. Finally, in its turn, the group of semiconductor transducers contains, in addition to InSb Hall plates, CdS photodetectors, GaAs pressure sensors etc., the very important group of silicon sensors.

The operation of these devices is based on the semiconducting properties of silicon. It is also possible to use silicon as a construction material for transducers, which exploits the silicon planar processing technology and the excellent mechanical properties of silicon, but not the semiconducting properties of silicon per se. The present problem, that there are not enough suitable transducers for the construction of new instruments, is being attacked from several sides. First an approach must be mentioned where the characteristics of present transducers are improved by adding signal-processing circuits. Today it is not difficult to correct a nonlinear dependence or an offset by the suitable programming of a microprocessor, as long as the nonideal characteristics are reproducible. Also, temperature sensitivity can easily be corrected. The transducer and the integrated circuit are often built together in a hybrid package. If both the transducer and the integrated circuit are mass produced and therefore inexpensive and the combination of both components yields a high quality transducer, the hybrid package might be a very commendable approach. However, when the above-mentioned solution is not possible, new materials or innovative uses of well-known effects are appropriate. The following section deals with nonsilicon generic technologies which are of current interest.

3.4.2 Generic Nonsilicon Technologies

Over the years a number of technologies have been introduced to fabricate solid state transducers. Some of these technologies are new because only now has the processing of these materials been mastered to a sufficient level, while other technologies are very old but have been continuously developed to reach the present state. The most important are presented below.

Piezoelectric materials

Certain classes of materials display the piezoelectric effect. A mechanical strain produces an electric polarization. In addition, the inverse effect, that is to say an electric polarization producing a strain or a dimension variation, also occurs in these materials. The materials are mainly suited to the construction of transducers in which the mechanical domain is converted to the electrical domain, but other signals can also be detected [6].

Quartz is the most frequently used piezoelectric material, but a number of piezoelectric ceramics are also often used. $LiNbO_3$ is a material which over the last decade has become rather popular in various applications. Increasing use is being made of polyvinylidenefluoride (PVDF), a piezoelectric polymer. Often, one of the advantages of piezoelectric transducers is that the measurand is converted into a frequency which can be measured with great accuracy. Because the resonance frequency for certain quartz platelets is a function of the temperature, quartz thermometers can be constructed.

Another device in which the piezoelectric effect can be used is based on surface acoustic wave propagation. The speed of propagation can be modulated by many parameters, such as strain, temperature, fluid density, causing, in turn, phase changes which can be detected with great accuracy.

Some allied crystals show pyroelectricity which means that a change of polarization occurs when the temperature changes. Very sensitive transducers for the measurement of temperature can be made with these materials.

Polymers

The conductivity, permittivity or mass of certain polymers changes slightly when they are inserted into certain gas atmospheres [7]. The electrical properties can be measured by constructing sandwich capacitors or by covering interdigital electrode patterns with the polymer. Sensitivity to CO, CO_2, CH_4 and moisture has been demonstrated. Polymers are increasingly being used, often together with silicon read-out, for applications such as detection of atmospheric pollutants and measurement of humidity.

Metal oxides

Much work is in progress in the field of gas-sensitive metal oxides [8]. At present the mechanisms are not very well understood; none the less, there are a few materials on the market that under certain circumstances can be used to fabricate reliable sensors. Materials such as SnO, ZrO_2, WO_3 and ZnO, with or without catalysts, show sensitivities to H_2, H_2O, O_2, CO and CH_4. Once our understanding and the technology of metal oxides have improved, they might provide us with a new class of useful, low-cost gas sensors.

III–V and II–VI semiconductors

Materials such as GaAs, GaP, AlSb, InSb, InAs, CdS, CdSe, ZnO and ZnS are semiconductors. In most cases, when a semiconductor is required for the fabrication of a transducer, silicon is used because the technology is very well known and allows batch fabrication. However, sometimes silicon does not have the appropriate physical effects. Therefore, when a direct band gap or a piezoelectric semiconductor is required, GaAs is used, instead of Si

[9]. When a high-mobility material is required InSb is a much better choice than Si. When a larger band gap is desirable the use of CdS may be preferable to that of Si. It is also possible to deposit these III–V and II–VI materials on Si substrates, thereby creating opportunities for developing new devices.

Thick- and thin-film materials

There are several techniques for depositing thin layers of resistive, piezoelectric, semiconducting or magnetic materials on suitable substrates. These layers often display the same effect as the bulk material which offers the advantage of being easily combined with electronic circuits in hybrid packages [10]. For almost all of the signal domains, well-functioning transducers have been made. Thin-film NiCr strain gauges, platinum temperature sensors, capacitive aluminum displacement sensors, thick-film thermistors, thin Ni–Fe film magnetic recording heads, thick-film pH sensors, thin-film thermocouples, etc. have now been comercialized. Because thin and thick films often do not require expensive processing instruments, these techniques are often suitable for use in the fabrication of transducers when only a small series is required.

Optical glass fibers

Optical glass fibers are being investigated in connection with their use in optical communication systems. It has been proven that transmission along fibers is influenced by a number of perturbations; consequently research is being focused on materials and structures that do not show these effects. One spin-off of this research was that scientists working in the transducer field have discovered that glass fibers can also be used to construct very sensitive and convenient transducers [11]. Temperature changes and mechanical perturbations cause polarization and phase changes which can be easily detected. For instance, chemical sensors can be made as the optical properties of the cladding influence the transmission properties of the fiber.

3.4.3 Silicon

Over the last four decades the progress in silicon planar technology has exceeded the most daring predictions. The result is that now we have a large number of very sophisticated VLSI components with an amazingly good performance/price ratio at our disposal. As mentioned above, the development in the transducer field was less dramatic, so that at present the introduction of microelectronics in many new application areas is being hampered by the lack of transducers with a good performance/price ratio. It seems, therefore, sensible to apply silicon planar technology to the transducer field as well, for instance, to develop chips that are sensitive to, say, pressure, temperature, flow, etc. [12]. The use of silicon not only makes it possible to apply the highly developed and sophisticated batch production methods of integrated circuits to the transducer field, but also makes it feasible to combine sensors and integrated circuits on one single chip. Such sensors are sometimes called ‘smart sensors’ or ‘intelligent transducers’, as introduced in Chapter 1.

Work on silicon transducers started many years ago. Since the 1960s, silicon has been used for the detection of light and there is an extensive literature on these devices. In early work, silicon was also used for the measurement of temperature, pressure and magnetic field. Today many research groups are now active in this field, which is one of the reasons for writing this text [13]. If we wish to use silicon as a transducer material, it is important to find out which of the physical effects that occur in silicon can be used in the conversion of the signal form.

Many physical effects occur in silicon, but predictably the element silicon does not display the same variety of effects as do all the other solid state materials combined. Yet on studying the effects in silicon we have found that this element is rather versatile. In Table 3.4 the most important effects which occur in silicon are presented [14].

The effects are divided into those used in self-generating transducers and those used in modulating transducers. A careful study of this table might at first glance lead one to believe that some effects in the table are not properly placed. For instance, the Nernst effect is placed in the box of a self-generating transducer which converts a thermal signal into an electrical signal. The Nernst effect is a thermoelectric (or thermomagnetic) phenomenon observed when a sample allowing electrical conduction is subjected to a magnetic field and a temperature gradient normal to each other. An electric field will be induced normal to both. Mobile energy carriers, such as electrons in the conduction band will move along temperature gradients due to statistics and the relationship between temperature and kinetic energy. If there is a magnetic field transversal to the temperature gradient and the carriers are electrically charged, they experience a force perpendicular to their direction of motion (the same as the direction of the temperature gradient) and to the magnetic field. Thus, a perpendicular electric field is induced.

The main energy flow is from thermal to electrical and the measurand is the thermal gradient. Because the input energy also carries the input signal, the transducer is of the self-generating type. The magnetic field is a necessity to ensure the conversion but is, in general, not an input signal. However, when for one reason or another we wish, in an innovative application of the Nernst effect, to measure a magnetic field with this effect, the transducer has to be regarded as a modulating transducer. The measurand modulates the conversion from thermal energy into electrical energy.

Silicon shows a number of very useful effects, but from Table 3.4 it is clear that silicon cannot be used when a self-generating transducer is required to convert signals from the mechanical or magnetic signal domain. Silicon is not a piezoelectric material because of its symmetrical lattice structure and, moreover, it is also nonmagnetic. To overcome this disadvantage it is sometimes possible to deposit layers on top of the silicon substrate, employing

Table 3.4 Physical and chemical effects in silicon

Signal domain	Self-generating effect	Modulating effect
Radiant	Photovoltaic effect	Photoconductivity Photoelectric effect
Mechanical	Acoustoelectric effect	Piezoresistivity Lateral photovoltaic Lateral photoelectric
Thermal	Seebeck effect Nernst effect	TCR
Magnetic		Hall effect Magnetoresistance Suhl effect
Chemical	Galvanic effect	Electrolytic conduction

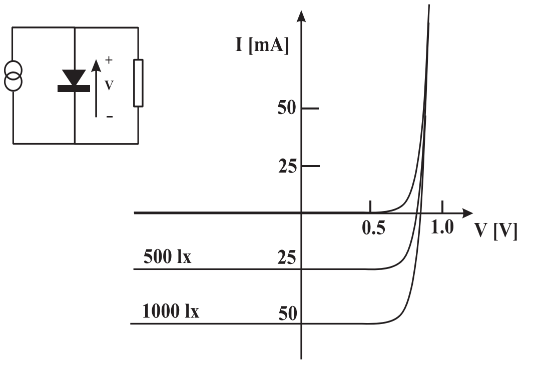


Figure 3.6 *I–V* characteristics of a photodiode with and without illumination

processing steps which are compatible with the standard silicon planar process. For example, a piezoelectric ZnO film can be deposited on silicon in order to construct a piezoelectric transducer. In the magnetic signal domain a similar solution is possible.

Even when silicon shows the required effect, it is possible that the frequency range, the light spectrum and the sensitivity would not be appropriate. However, in these cases as well, deposited layers could be the solution.

3.5 Examples of Silicon Sensors

3.5.1 Radiation Domain

Many silicon-based radiation sensors rely on the generation of electron–hole pairs, often within a p–n junction depletion layer [15]. When electron–hole pairs are generated in the depletion region, the built-in electric field separates them to where they are majority carriers, with less chance to recombine. This creates a shift in the *I–V* characteristics of a diode as shown in Figure 3.6.

Four examples of junction-based radiation sensors are given in Figure 3.7.

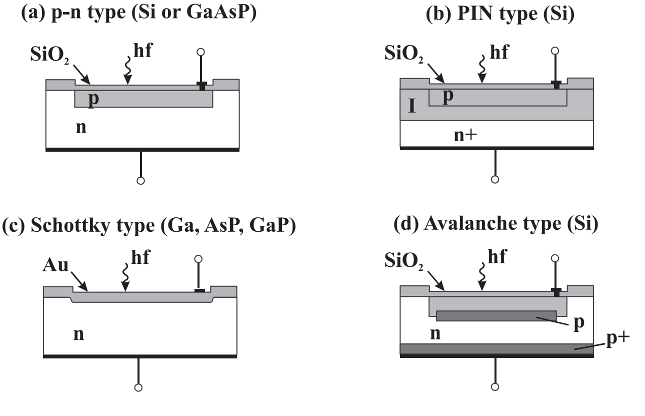


Figure 3.7 Junction-based radiation sensors

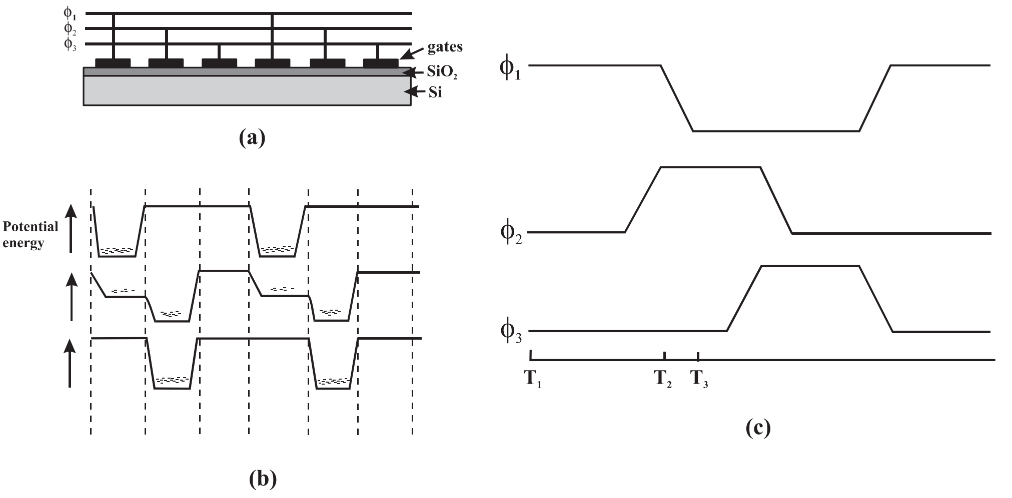


Figure 3.8 CCD array: (a) wiring, (b) shifting of the potential well and (c) driving signal

The penetration depth of the light in silicon is highly dependent upon the wavelength, particularly in the visible range. Shorter wavelength light, with higher energy photons (blue light), has high absorption and is all absorbed close to the surface of the silicon. As the wavelength increases the absorption rate is reduced until we reach infrared, where silicon is transparent and the light passes through. More details can be found in Chapter 4.

A major breakthrough for digital photography has been the charge coupled device (CCD). The CCD itself is an extremely simple device which is the reason it has been possible to develop high density arrays [16]. The CCD started life in 1969 as an attempt to make a memory array at the Bell labs. Its inventors were William Boyle and George Smith. It soon became clear that the charge could be generated using the photoelectric effect and the CCD was born. The simplicity of the device made it easy to produce large arrays with a simple read-out. The sequence of read-out is given in Figure 3.8.

In addition to radiation measurement, radiation sensors are also often applied to other domains such as position. The PSD (position sensitive detector) determines a position or rotation through measuring the location of a light spot on a p–n junction where the contacts are all on the edge. This is illustrated in Figure 3.9.

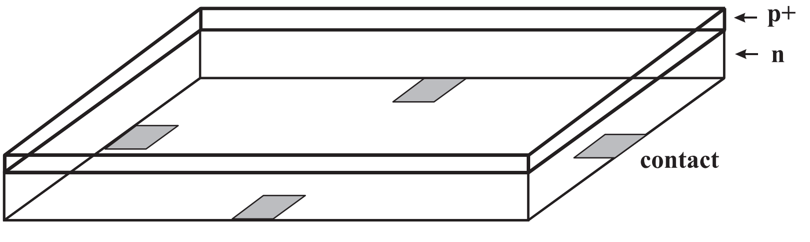


Figure 3.9 Simple PSD device

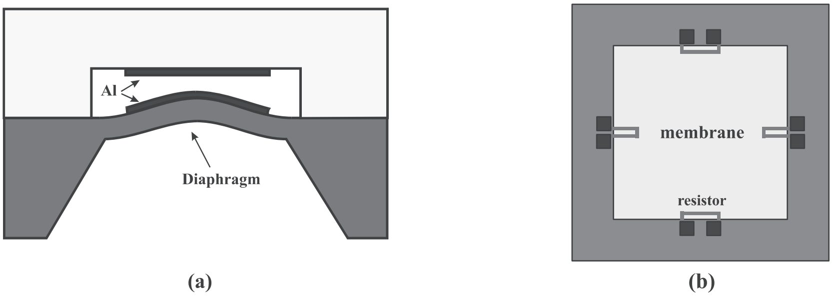


Figure 3.10 (a) Capacitive pressure sensor and (b) piezoresistive pressure sensor

3.5.2 Mechanical Domain

The two main applications for silicon mechanical sensors are pressure and acceleration, although recent years have seen an increase in commercial silicon gyroscopes. The pressure sensor is usually based on a membrane where either the bending of the membrane or the stress on the surface is used to measure stress [17, 18]. This basic device is given in Figure 3.10.

The accelerometer is based on a mass and a spring and here the read-out can also be based on displacement or stress. An example of a capacitive-based device is given in Figure 3.11.

The device which gave a boost to silicon sensors in the automotive industry was the airbag. To detect a crash an accelerometer is used whereby a high deceleration is interpreted as a collision. The advantage of silicon is the ability to introduce a self-test. The self-test is a technique where the mass can be moved through integrated actuation and the movement measured to test the operation of the device. Some early devices used thermal activation. Smaller devices, such as these shown in Figure 3.12, lend themselves very well to electrostatic activation. In this case the extra electrodes are used to move the mass electrostatically and the normal read-out circuitry is used to test whether the mass moves correctly. For this safety critical application, this addtional feature was a major breakthrough.

3.5.3 Thermal Domain

It is often observed that many sensors for other domains have an unwanted temperature sensitivity. This may appear to indicate that a temperature sensor is easy to achieve. However, the

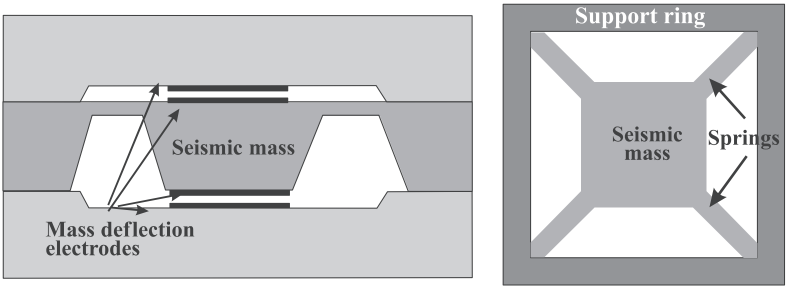
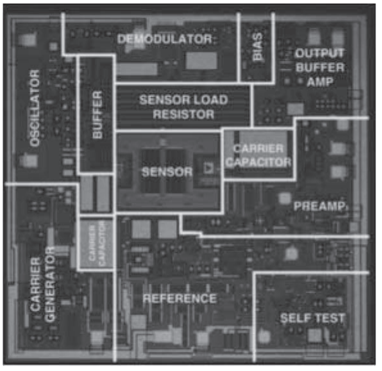


Figure 3.11 Capacitive read-out vertical accelerometer



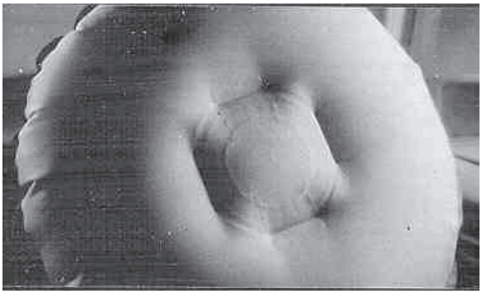


Figure 3.12 (*left*) Analog Devices ADXL50 (Copyright Analog Devices, Inc. All Rights Reserved) (*right*) an activated airbag

development of an accurate temperature sensor is more complicated. The platinum resistor is often used as a temperature sensor because of its stability over a wide temperature range. The thermopile can be used to measure temperature differences, which will be discussed below. Within electronic circuitry many elements are temperature sensitive. This has been put to good use in a CMOS temperature sensor where the sensor element is based on a p–n junction [19]. This device is illustrated in Figure 3.13. A more detailed discussion of temperature sensors can be found in Chapter 7.

Although the most obvious form for the thermal domain is to measure temperature, many thermal sensors are used to measure other parameters such as flow and vacuum. The flow sensor uses a simple principle where the chip is heated by a resistor and the temperature difference up wind and down wind is measured. The difference is a direct measure of the flow, although the heat conduction of the gas and fluid in the flow needs to be taken into

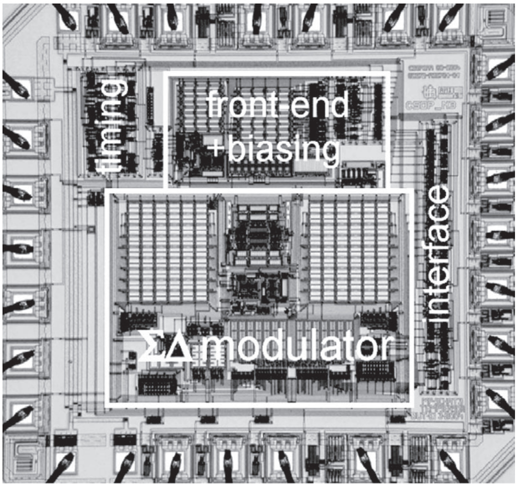


Figure 3.13 Fully integrated CMOS temperature sensor

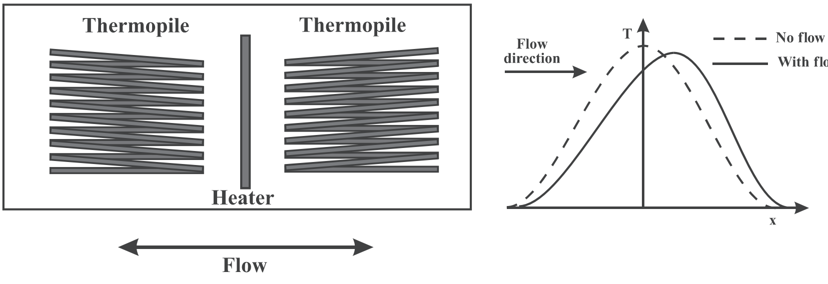


Figure 3.14 Thermal flow sensor

account. An example of one of these devices is given in Figure 3.14. This can be extended to a two-dimensional device for wind measurement. The example given in Figure 3.15 [20].

A range of applications of thermal techniques to measure nonthermal parameters can be found in Chapter 6.

3.5.4 Magnetic Domain

The basis of many of magnetic sensors is the Hall effect, which is the deflection of carriers perpendicular to a magnetic field [21]. In its simplest form this can be read out using a Hall plate, as illustrated in Figure 3.16.

In addition to determining the direction and magnitude of magnetic field, Hall plates are often applied to measuring current, rotation and position. An example of a current sensor is given in Figure 3.17.

A simple but effective example of a silicon sensor is the Hall sensor for measuring rotation. This is shown in Figure 3.18. The tooth wheel attached to the axis modulates the magnetic

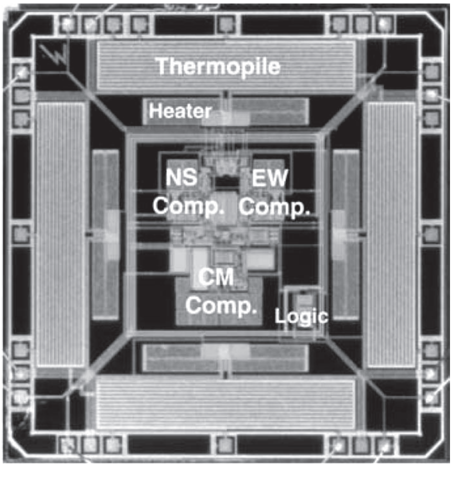


Figure 3.15 Fully integrated smart wind sensor

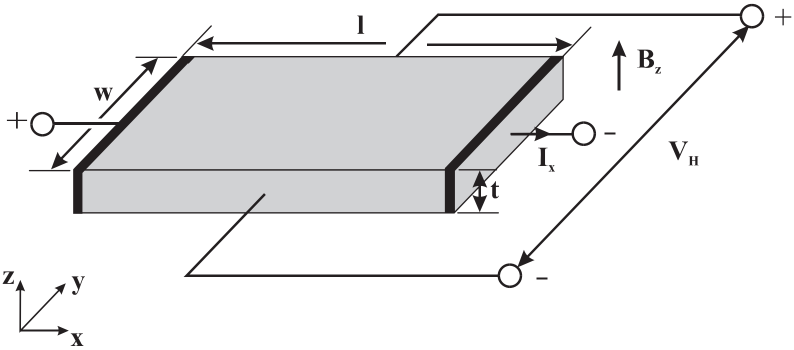


Figure 3.16 Basic Hall plate for measuring magnetic field

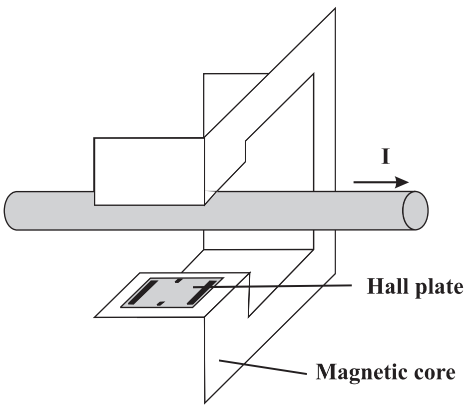


Figure 3.17 Magnetic sensor technique for measuring current

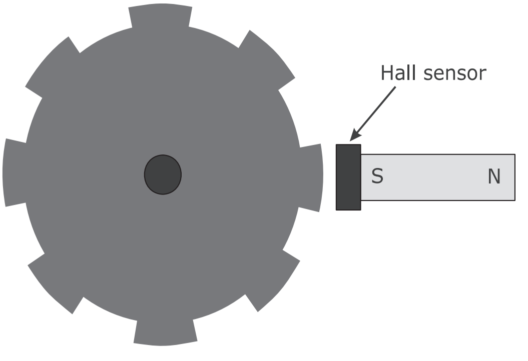


Figure 3.18 Rotation sensor using a Hall device

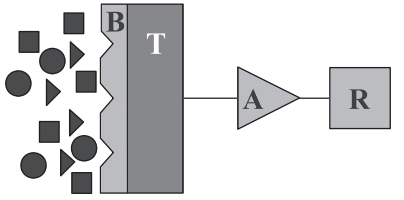


Figure 3.19 Trapping of elements at the surface of the sensor using a special coating

field through the Hall sensor thus giving pulses which can be converted into a measure of rotation. Detailed discussion of integrated Hall sensors is given in Chapter 9.

3.5.5 Chemical Domain

In the chemical domain, many devices have to create a chemical reaction or trap ions/molecules at the surface. The trapping at the surface is shown schematically in Figure 3.19. Some chemical sensors rely on a chemical reaction to detect the desired elements. An example of this is the Clark cell shown in Figure 3.20 [22, 23]. The membrane is designed to allow oxygen to pass through. When a voltage is applied between the two electrodes, the oxygen in the electrolyte reacts with the silver electrode to produce AgCl. The higher the oxygen concentration the higher the current. This is an effective technique for measuring oxygen but the lifetime of the sensor is limited by the reaction. However, for many applications this is not a problem.

An alternative approach is to use what is called a physical-chemosensor (see Chapter 5 for more details). In this case physical measurementns are used to obtain chemical parameters [24]. For example, viscosity or density measurements of a liquid can give information on concentration. Such a device has been developed in Delft where density measurements using surface acoustic waves (SAW) have been used to measure alcohol concentration in water. The SAW devices generate waves in the membrane which are received at the other end of the chip, as shown in Figure 3.21. The input electrode, on the left-hand side, generates mechanical movement in the layer below, which is a piezoelectric material. The movement travels in the form of a wave to the right-hand side, where the movement is converted back to an electrical

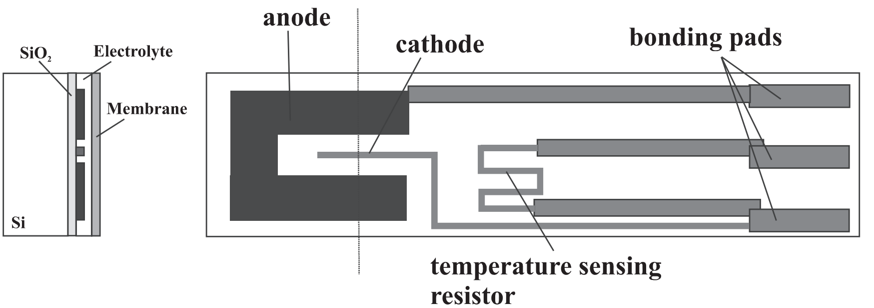


Figure 3.20 The Clark cell for measuring oxygen levels

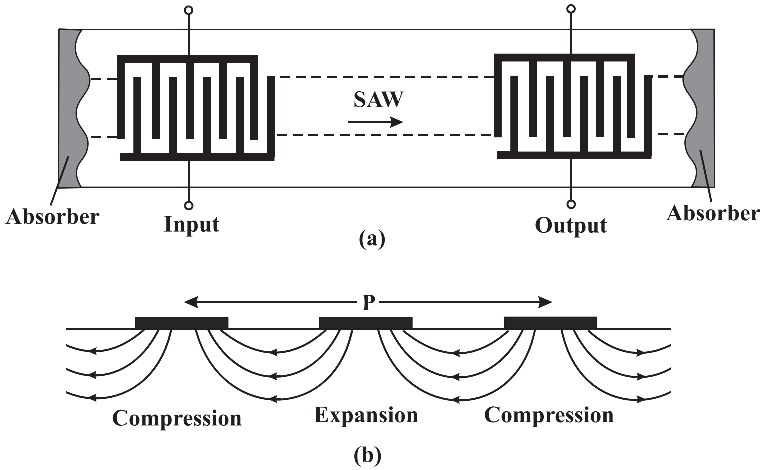


Figure 3.21 Planar and cross-sectional view of a SAW device

signal. If this travels across a thin membrane in contact with a fluid, the density of the fluid will affect the propagation speed of the wave. This in turn can be measured.

3.6 Summary and Future Trends

3.6.1 Summary

In this chapter the importance of sensors in modern society has been shown. The use of silicon offers many opportunities to increase functionality while reducing the size of the system. For each of the signal domains physical effects can be found in silicon or in some cases, alternative materials combined with silicon. The future of silicon sensors will make further use of the developments in the IC industry as the size of the system is further reduced while functionality is expanded.

3.6.2 Future Trends

The silicon sensor device is already miniaturized and for many applications further miniaturization is either not necessary or will lead to deteriorating characteristics. However, in the case of some devices, further scaling into the nanoscale will open new possibilities.

For the true application of silicon sensors it is important to consider not only the sensing device but also the whole system. As sensors are being applied in harsh and/or remote environments, more autonomy will be required. Figure 3.22 gives a number of issues which will require attention as the devices become more autonomous. The issue listed are as follows:

- Communication – increased autonomy will require wireless communication.
- Supply – the use of batteries may limit the lifetime of devices where access is difficult. Transmitting power to the device, or scavenging energy from the environment, is a potential solution.

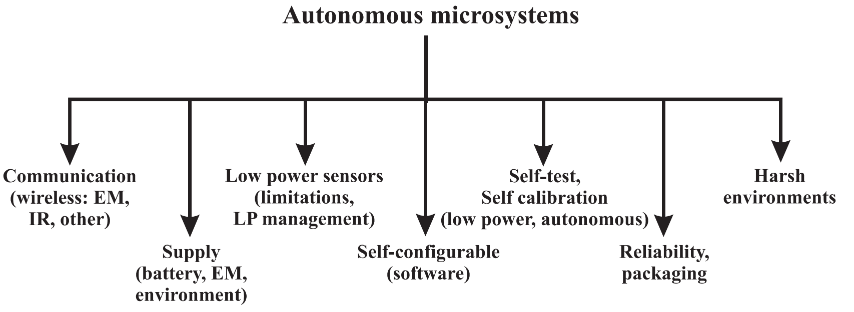


Figure 3.22 Autonomous microsystems

- Low-power sensors – when the power supply is limited, increased emphasis will be focused on reducing the sensor power consumption, including device management.
- Self-configurable – particularly important in remote locations, where the sensor system may have to adapt in hardware or software to a changing environment, or to compensate for a damaged device.
- Self-test, self-calibration – the introduction of self-test for airbag sensors was a breakthrough for this application. However, the next step will be where the device itself decides when to apply the test and how to react to the result.
- Reliability and packaging – this is a very important issue for the development of new sensors, particularly in harsh environments.
- Harsh environments – silicon sensors are increasingly being applied in harsh environment, in terms of temperature or chemically active.

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