APPLIED PHYSICS OF SEMICONDUCTORS: THE CASE OF SENSORS

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Abstract:

A sensor generally is a device which in a measuring procedure transforms a nonelectrical variable into a suitable electrical signal. Although the applied physics and measurement technology have dealt with them for more than a century, sensors became especially interesting with the availability of the sophisticated microprocessors. Compatibility with microprocessors and the capability of integration with them head the list of aims in the development of today's sensors. Since they are in whole or at least in part the semiconductor devices, the paper concentrates on the description of the role of physics and technology of semiconductors in their development.

INTRODUCTION

The aim of this article (and of the talk by the author at the Symposium) is to describe the present state of development of a diverse group of devices known as the sensors.They are the vital and indispensable components of almost all modern measuring and control systems. Their crucial role is to transform the detected or measured nonelectrical variables into appropriate electrical signals. The development of these environment-to--instrument interfaces is a notable example of interdisciplinary research, as it certainly benefited from advances in many sciences and technologies. However, the advances in the physics of semiconductors and in the semiconductor technology seem to have been the most important. Although the various types of sensors or, more generally, transducers, were developed to a high degree of perfection during the last hunderd years (thermocouples, microphones and inductive counters of rotation frequency are among the oldest examples), today's sensors are predominantly semiconductor devices. Moreover, a number of people today would be inclined to predict an especially important role for the „new" semiconductor sensors. The word „new" here signifies the compatibility with microprocessors and the capability of integration with them. This prediction is quite understandable. A microprocessor can monitor a wide variety of signals from the sensors and can vary their processing to a much greater extent than has previously been possible. Since microprocessors are already highly sophisticated as it is, the degree of sophistication of a measuring or control system will depend solely on the availability of simple, acurrate, reliable and compatible sensors. This is the reason for the growing interest in these devices during the last decade. There are so many different nonelectrical (physical, chemical, biological) variables to be measured in the various processes that an equally wide variety of the types of sensors is a necessity, further enhanced by the fact that the same variable often must be measured in different ways. The measurement of blood pressure in vivo, for example, is obviously a different problem than the measurement of the pressure of a corrosive vapour in an industrial process.

TERMINOLOGY

The position of a sensor in a measuring or control system is shown in Fig. 1. A nonelectrical time-dependent variable x(t) is first fed to the transducer, a device which usually combines a receptor and a sensor. In many cases where the receptor is lacking, however, the term transducer becomes equivalent with the term sensor. If, for example, a thermocopule is used to measure temperature, it may also be described as a transducer. But to measure the intensity of radiation it must be combined with an receptor: a small black disc which absorbs the radiation. The transducer is now a two-part device. Heating the disc, the radiation causes the temperature difference which is measured by the thermocouple. The rule is general: a receptor is a part of a transducer which transforms a nonelectrical variable x(t) into another nonelectrical variable, x'(t), more appropriate for the chosen sensor. As we said before, the sensor itself is the site of another transformation, in this case the transformation into a suitable electrical signal y(t) which is fed to the second part of the system – the processor. The duty of a processor is the conditioning of the signal: it amplifies y(t), extracts the noise from it, corrects the nonlinearities and drift, makes analog-to-digital transformation, etc. The conditioned signal z(t) is then used either for a direct measurement (case A) or, through an actuator, for a control purpose (case B). Since we are here interested in the physical, not electronical, aspects of the problem our attention will be devoted solely to the transducers, or even more specifically, to the sensors. Their functioning poses a number of very interesting problems to the applied physics.

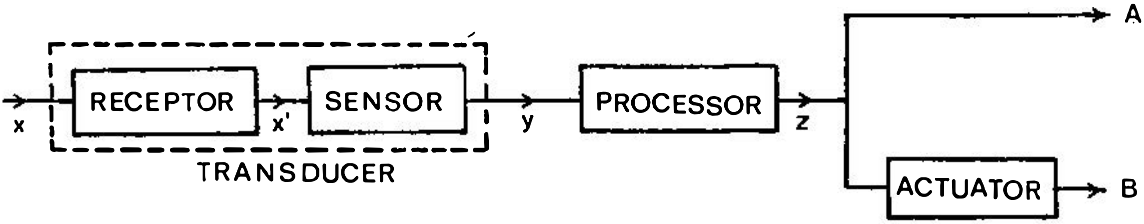

Fig. 1.
The place of sensor in a measuring or control system

Most generally sensors are divided into two distinct classes. In the first of them a nonelectrical variable x(t), or x'(t) is said to generate an electrical signal y(t). Light generates a voltage across a photovoltaic cell, heat generates a thermoelectric force, etc. Since in this case sensors are the places where the conversion of energy occurs they are called the active sensors. In the second class a nonelectrical varible does not generate an electrical signal but influences it. What we call the "signal" in this case is the change in resistance or capacitance or inductance of a sensor under the influence of temperature, mechanical deformation, magnetic field, etc. The sensors of this class are called passive sensors. The effects which may be involved in the functioning of either or both types of sensors are numerous. In the next paragraph we shall describe shortly the effects which are used most frequently.

THE EFFECTS

Piezoresistivity.[1] The properties of piezoresistive sensors are considered on the basis of a very simple equation. If the deformation of a part of a sensor may be treated as uniaxial the equation links the relative change of the length of the sample, dL/L, and the relative change of its resistance dR/R. Thus $dR/R=d\rho/\rho + (1+P)dL/L$. Here ρ is the resistivity of the sensor material and P is the Poisson's ratio. In the range of elastic deformation $d\rho/\rho$ is also proportional to dL/L, and the basic equation may be written in the form $dR/R=\gamma dL/L$ in which γ is the coefficient of piezoresistivity. A piezoresistive sensor (we cali it the strain-gauge) is evidently better if its γ is greater. While metallic strain-gauges have γ around 2, p-type silicon sensors have γ around 150. Such a high value of γ, combined with other excellent properties, makes silicon almost ideal for the micro-machined sensors of mechanical deformations, force, acceleration, pressure, etc. A further advantage of silicon lies in the fact that all these sensors may be produced by the well known planar technology. In fact, a piezoresistive sensor of pressure was the first to be integrated with a microprocessor, giving a very complex structure named "smart" or "inteligent" sensor[2].

Thermoresistivity. The influence of temperature on the resistivity of materials was probably the first effect to find application in the field of sensors. Indeed, except for thermocouples the resistance thermometers are the oldest devices for the precise and reliable measurement of temperature. Metals and semiconductors are both used in the production of resistance thermometers. The metals, have some definite advantages over the semiconductors. Platinum, for example, gives a linear response, may be used in a broad temperature range, and is chemically stable. But it is among the most expensive materials. On the other side, a special group of semiconductors, the thermistors, has been designed for temperature sensors. The resistivity of thermistors is much more sensitive to temperature changes than the resistivity of metals, but the relationship is exponential rather than linear. Today this is considered inconvenient and the thermistors outdated, except for special applications. Modern semiconductor sensors have a linear response with the positive temperature coefficient of resistivity and work in the so-called exhaustion range of conductivity. Here R(T) is not governed by the concentration of charge carriers, but by their mobility. The most frequent devices of this type are silicon sensors, produced by planar technology in the so called "spreading resistance" configuration[3]. Their drawback, however, is the relatively narrow range of working temperatures: from –50 to +150°C. To broaden the range particularly towards the higher temperatures without the change of configuration some other semiconducting material must be employed. The field is not well investigated as yet, however. Very high temperatures are still measured predominantly with the metallic sensors or with the new types of thermistors based on the ionic conductivity of some solid electrolytes[4].

Magnetoresistivity. It is well known that the resistance of a semiconductor sample is dependent on the strength of the magnetic field. For transversal effect, when the current through the sample is perpendicular to the magnetic field B, the change of sample's resistivity may be described by the equation $\Delta\rho/\rho = DB^2$, in which factor D reflects the nature of the semiconductor, the type of scattering of charge carriers, the sample shape, and the magnetic field. For weak fields ($\mu B << 1$, where μ is the carrier mobility) in nondegenerate semiconductors with scalar effective masses and phonon scattering, this equation may be written in the form $\Delta\rho/\rho = 0.38\,\mu^2 B^2$. Thus the semiconductors with the larger mobility of carriers are more suitable for the field sunsing devices. At the same time the carrier mobility, through the expression $\mu B >> 1$, defines the „strong fields" where the magnetoresistivity tends to saturate at about 13%. If the effective masses are tensor quantities the situation is more complicated because of the anisotropy of magnetoresistivity. It is important to know that Hall effect decreases the effect of magnetoresistivity. The influence of Hall effect may be neglected only in the samples of unlimited dimensions. In sensor design this suggests a simulation of such samples: the short-circuiting of Hall probes or the use of Corbino discs.

Photoresistivity. This effect[5], discovered early in the history of semiconductor physics, found a distinct place in the sensor application. The photoresistors, as such sensors are known, aim to detect the various kinds of radiation. Here the electrical signal is the change of resistivity of a semiconductor due to the excitation of charge carriers from one band (or impurity level) to the other. In the simplest case of band-to-band transitions the energy of the photons to be detected should be higher than the energy gap of the semiconductor involved. Silicon, for example, with its gap equal to 1.1 eV is able to detect the radiation with the wave length of under 1000 nm. There is, however, a number of binary or ternary semiconductor compounds able to detect the radiation of longer wave lengths. It should be stressed that despite the apparent simplicity of the photoresistive effect the technology involved here is not simple at all. Infrared sensors, especially those for military applications, are very sophisticated and expensive.

Surface Resistivity. Sensors based on the fact that some gases, and notably the combustible gases, dramaticaly change the surface resistivity of metal oxides (SnO_2, ZnO, Wo_3, etc.)[6], are probably the most interesting commercially. They have been produced in millions. Curiously, the mechanisms behind their gas sensitivity are not understood in great detail and only a crude explanation can be given here. In short, when the surface of a metal oxide is covered by chemisorbed oxygen the electrons become localized at the surface, giving a very low surface conductivity. When the material is exposed to a gas which reacts with the chemisorbed oxygen, the conductivity sharply increases due to the decreased amount of oxygen at the surface. The process is reversible and — at temperatures above, say, 100°C — fast enough to be used for gas detection. The main drawback of these sensors is a rather poor selectivity. The reactivity for specific gases can be increased by the addition of some catalytic substances to the sensor but such improvements are largely empirical. For this reason many fundamental studies of the catalytic reactions are currently being carried out to gain better understanding of the processes involved. The same can be said for polymer gas detectors, e.g. for the sensors of ammonia, made or polypirrole.[7]

Piezoelectric Effect. This effect is of great value for the technology of sensors, as can be illustrated by many examples. The improvements in electroacustical devices brought by the "crystal" pick-ups and "crystal" microphones are probably the best known. Particularly important today are the quartz resonator sensors, originally developed for use as frequency standards in electronic instruments and digital clocks and watches. Thus a number of piezoelectric sensors have been introduced for the measurement of force, pressure, flow, etc. A special advantage of these sensors is their ability to give an intrinsically digital output. Besides the "normal" modes of oscillation the so-called surface acoustic waves have an increasing role in the construction of many classes of new sensors. Some other aspects of vibrational sensors will be described in the last paragraph.

Photovoltaic Effect. Besides the passive sensors of radiation, the photoresistors, there is also a group of active sensors of the same variable: photodiodes and phototransistors. They are based on the photovoltaic effect in semiconductor structures, like Schottky barriers and p-n junctions[5]. While the earliest devices employed selenium, today the silicon photodevices are dominant. They are used for various types of sensing, either directly or in combination with light-emitting diodes or semiconductor lasers, i.e. with the devices based on the radiative recombination, the effect which is inverse to the photovoltaic effect.

Seebeck and Peltier Effects. Despite the fact that the values of Seebeck coefficients of semiconductors are much larger than those of metals, semiconductor thermocouples are but rarely used. When the thermocouple appears to be the most appropriate sensor for the measurement of temperature, or some temperature-related quantity, the use of metallic only thermocouples is the common practice. In the range of high temperatures it is the rule. The properties of semiconductors become much more important should the inverse Seebeck effect, or Peltier effect, be involved in the functioning of a sensor. Indeed, the Peltier devices are included in many complex sensors in which a simple way of cooling is necessary. The measurement of humidity via the dew point is a good example.

Hall Effect. Hall effect sensors, or hallotrons as they are sometimes called, are among the best known sensors. There are no serious problems either with the theory of Hall effect in semiconductors or with the technology of hallotrons, and various sensors of this type are commercially available. They are used in the measurement of magnetic field, strong currents, distances, levels etc. Silicon is the most popular material, but the semiconductors with a higher mobility of charge carriers are sometimes more appropriate. In such cases InSb or GaAs are often the most suitable. It should be mentioned here that Hall effect also plays an important role in metrology. The recently discovered quantum Hall effect is apparently a basic effect in the determination of some fundamental constants.

Field-effect. Transistors are most often used as amplifying or switching devices. They may also serve as sensors, however. If, for example, the collector current of a bipolar transistor is held at a constant value, the voltage between the base and the emitter increases with temperature. Thus a bipolar transistor may be used as a temperature sensor. But it seems that unipolar or field-effect transistors (FET) will find much wider application, especially in the sensing of chemical quantities[8]. Such devices are called CHEMFET. A silicon CHEMFET is a FET whose base (a metallic layer deposited on SiO_2 or the SiO_2/Si_3N passivation layer) is immersed in a solution and connected to the measuring circuit through a standard electrode. The souce-to-drain current is dependent on the concentration of H^+ ions adsorbed on the gate layer, meaning that a specially prepared FET may be used as a pH—sensor. In more sophisticated versions the metallic gate is combined with various active layers, ion-selective membranes (ISFET) or immobilized enzymes (ENFET), making the transistor able to recognize not just the simple ions like Na^+ or K^+, but some very complicated molecules (e.g. urea) as well. Finally, a FET with the gate layer made of palladium (PdFET) has been designed to measure the concentration of hidrogen or gaseous hidrogen compounds.

THE COMPLEXITY OF SENSORS

In contrast to some other electronic devices the sensors and transducers appear in a great variety of sorts and types. A single type of sensor combined with the various receptors may give a great number of different transducers. In some of them the roles of sensor and receptor cannot be distinquished clearly. In the effort to make the complicated picture simpler the authors of some reviews have introduced the various classifications of sensors. In most of them, however, the difference between the terms "sensor" and "transducer" is unclear. Sensors by themselves, as well as the combinations of sensor and receptor are often simply called "sensors". While the sensors themselves are easily classified according to the effects described in the previous paragraph, such classification is of scant use since the measuring devices (called "sensors" in this simplified jargon) most often complex transducers.

Apart from this intrinsic complexity, one can speak of sensor complexity of a higher level. The reason for this is twofold. First, no known sensor will respond to just a single particular nonelectrical variable. It is always sensitive to two or more variables. Except for the one we want to determine, all the others are disturbances that must be compensated for in some way. Thus a sophisticated "sensor" may be seen as the combination of sensor and the compensating elements "integrated" in a single structure. This is the first step in the design of "smart" or "intelligent" sensors.

The second group of complex sensors are so-called multisensors. Their complexity stems from the requirement for the simultaneous determination of two or more variables. Together with the elements for the compensation of unwanted variables the multisensors are really complex devices. As we shall see in the next paragraph they are specially designed for the use in medicine.

THREE GROUPS OF MODERN SENSORS

The present situation in the sensor development suggests that the following three groups of complex sensors deserve special attention. They are likely to play a major role in the future development of sensors. They are the optical (or optoelectronic) sensors, vibrational (or resonator) sensors, and microelectronic sensors.

Optical Sensors. The most advanced versions of optical sensors are so-called optical fiber sensors[9]. Let us describe their main features. Generally, a fiber sensor is a piece of optical fiber with a source of light (LED or semiconductor laser) at one end and a photodetector at the other end. A nonelectrical variable to be determined is allowed to modulate the light passing through the fiber. There are two ways of modulation: external and internal. The sensors with external modulation consist in fact of two pieces of fiber. One is a light emitter, the other is a pick-up for the light reflected on, or transmited through, a medium. What we call "modulation" is a change in reflectivity or transmitivity of the medium caused by the variable to be determined. This is a principle on which a number of sensors are designed (torque, position, temperature, concentration of fine particles in the air, etc.) Many of them are still in the development stage. In the second case the light is modulated internally. The sensor is constructed in such a way that the light is allowed to pass outside the fiber under certain condition, determined by the quantity to be measured. It may either vary the optical properties of the fiber's environment (as in the measurements of the composition or density) or cause the bending of the fiber (as in the measurements of pressure or force). Since the two ways of modulation offer many other possibilities for the construction of sensors this is the field of great current interest. Despite the fact that they are often in competition with other types of sensors, their versatility and smaller sensitivity to noise give them a prominent future, especially for medical applications. They can be made small, noncorrosive and compatible with the living tissue. Finally, they are easily designed as multisensors. A good example of this is a multisensor able to measure the blood pressure, pulse, pO_2 and pCO_2 simultaneously.

Vibrational sensors. The sensors of this type measure the resonant frequency of a mechanical structure (a magnetically driven wire, a vane with piezoelectric transducers) and relate it to the property to be determined[10]. As we said above the development of such sensors is particularly encouraged by the fact that they are able to produce intrinsically digital signals. This is an important facet of the compatibility of sensors with the microprocessors. A good example is the quartz oscillator as frequency standards in electronic instruments and digital clocks. But there are many other, more complex vibrational sensors. The flow of liquids, for example, can be computed from the measurements of the resonant frequency of a vibrating vane imersed in the flowing liquid and the phase difference induced along the vane. Some other quantities, like acceleration, force, pressure, viscosity and density of liquids, can be measured with similar sensors. Simultaneous measurement of two or more variables is also possible. In most cases today's vibrational sensors are the structures driven by piezoelectric transducers. Since they are limited in operation to about 350°C, magnetically driven wires are likely to be employed over larger temperature intervals. Thus the availability of new materials with stable and repeatable mechanical properties become more and more important.

Microelectronic sensors. As already mentioned, the semiconductor, and especially the silicon technology, had a considerable influence on the development of new sensors. Some of the most advanced "inteligent" sensors are microelectronic sensors produced wholy by the well known planar technology. Thus a microelectronic pressure sensor consists of a thin diaphragm of about 1 mm in diameter, etched in an n-type silicon wafer. A Wheatstone bridge of four p-type resistors is diffused into the diaphragm and connected to the adjacent microprocessor. The deflection of the diaphragm causes the change in the piezoresistivity of the resistors and generates an electrical signal which is fed to the microprocessor and conditioned. While such examples of fully integrated transducers are still relatively rare, the range of discrete microelectronic sensors is much wider. Let us mention only the various types of CHEMFET, as the typical discrete devices, and the semiconductor light emitting diodes and lasers as the vital components of the already described optical fiber sensors.

CONCLUSION

As defined in the abstract of this article the sensors are inevitable parts of modern electronic measuring and control systems. In an ideal situation one would expect that for any physical parameter to be measured or detected there should be a sensor able to convert it to a signal digestible by an electronic system. But despite a great variety of sensors already developed the situation is far from ideal. The problems of reliability, accuracy, range of applications, stability and many other subtle performance qualities are still with us. Last but not least, there is a problem of the price. The last decade has seen a spate of activity in the field of sensors. New opportunities are opened by the development of new materials and by the scientific contributions from physics, chemistry, biology and information science. Conversely, the sensors are of growing importance for the sophistication of experiment in these sciences. In short, the field of sensors presents a great challenge for the technologists and for the physicists inclined towards applied research, since the range of sciences and technologies potentially interested in the field is almost overwhelming.

REFERENCES

1. See, for example, K. Seeger, Semiconductor Physics, Springer, Wien-New York 1973, p. 136.
2. R. Allan, High Technology, September 1984, p. 255.
3. R.G. Mazur and D.N. Dickey, J. Electrochem. Soc., March 1966, p. 235.
4. E.G. Wolff, Rev. Sci. Instr, April 1969, p. 544.
5. J.I. Pankove, Optical Processes in Semiconductors, Dover, New York 1975.
6. C.Nylander, J. Phys. E, September 1985, p. 736.
7. C. Nylander, M. Armgarth and I. Lundstrom, Proc. Int. Meeting on Chem. Sensors, Elsevier, Amsterdam 1983, p. 203
8. C.E. Marsham, Phys. Bull., October 1986, p. 296.
9. T.G. Giallorenzi et al, IEEE Spectrum, September 1986, p. 44.
10. G.R. Jordan, J. Phys. E, September 1986, p. 729.