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Andrea De Marcellis
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Analog Circuits and Systems for Voltage-Mode and Current-Mode Sensor Interfacing Applications

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Preface

This book proposes recent scientific results concerning the research of novel electronic integrated circuits and system solutions for sensor interfacing, many of which developed by the authors, utilizing the deep experience in analog microelectronics of the research team from University of L'Aquila both in sensor field and in Low Voltage Low Power analog integrated circuit design with Voltage-Mode and Current-Mode approaches. In particular, this monograph describes and discusses a number of analog interfaces, suitable for resistive, capacitive and temperature sensors, some of which developed by the authors also in a standard *CMOS* integrated technology (AMS 0.35 μm).

The book is organized as follows.

After a fast "excursus" on physical and chemical sensors (Chap. 1) and a state of art analysis of the main resistive, capacitive and temperature sensors and their related basic analog interfaces (Chap. 2), novel and improved solutions of Low Voltage Low Power analog circuits and systems, designed both in Voltage-Mode (Chap. 3) and in Current-Mode (Chap. 4) approaches, suitable for portable sensor interfacing applications, will be described and investigated. Then, the lock-in technique will be considered (Chap. 5) with the aim to improve the sensor system characteristics. In the Appendices, the Second Generation Current Conveyor theory and applications, together with some novel design implementations at transistor level, as well as the noise and offset compensation techniques for the design of high-accuracy instrumentation voltage amplifiers, will be also described.

More in detail, concerning resistive sensors, the book describes the main design aspects and different circuit solutions of the first analog front-ends, performing resistance-to-voltage (for small measurand variations) and resistance-to-period or frequency (for wide variation ranges) conversions, both in Voltage-Mode and in Current-Mode approaches and using AC as well as DC excitation voltages for the sensors; also, it has been proved that the analog lock-in amplifier can be employed for enhancing resistive sensor system sensitivity and resolution.

Regarding capacitive sensors, both the Voltage-Mode and the Current-Mode approaches have been utilized to develop suitable interface systems converting the capacitance change of the sensing element into a voltage or a frequency variation.

Moreover, temperature sensors and their interfaces have been described. They have proved to be necessary in many sensor systems, since their characteristics are strictly related to operating thermal conditions. In this sense, electronic heater circuits for temperature control are shown.

We want to mention the fact that after an accurate design by means of a suitable simulation software, as ORCAD PSpice and CADENCE Virtuoso-Affirma, some of the described circuits (in particular, those developed by the authors of this book) have been implemented through prototype boards, with commercial discrete components, so to characterize and validate the new ideas, studying also other possible improvements. The final step has been, in some cases, the fabrication of the integrated circuit on-chip, in a standard *CMOS* technology, which follows the implementation of the circuit layout.

This book originated from the Ph.D. final dissertation of the first author and wants to give an overview of Voltage-Mode and Current-Mode analog sensor interfaces. In our opinion, it can be useful for analog electronic circuit designers, as well as for sensor companies, but can be also utilized as reference text book in advanced graduate or Ph.D. courses covering these topics. In this sense, the presented interfaces can be easily fabricated both as prototype boards, for a fast characterization (in this sense, they can be simply implemented by students and technicians), and as integrated circuits, also using modern design techniques (well known to specialist analog microelectronic students and designers).

We hope that this book will be interested and useful for readers at the same level of which it has been exciting and difficult to write it.

Furthermore, we want to address some acknowledgements. In particular, we want to thank Prof. Arnaldo D'Amico (University of Roma Tor Vergata) to have been an invaluable reference in all our working and scientific research activities. Then, we thank all the people with whom we have collaborated and discussed, at different levels, in particular, in an alphabetic order, Carlo Cantalini, Alessandro Depari, Claudia Di Carlo, Corrado Di Natale, Christian Falconi, Ferdinando Feliciangeli, Alessandra Flammini, Fabrizio Mancini, Paolo Mantenuto, Daniele Marioli, Eugenio Martinelli, Roberto Paolesse, Andrea Pelliccione, Stefano Ricci, Emiliano Sisinni, Vincenzo Stornelli and all the students who helped us to develop, simulate and test some of the described circuits.

Finally, we would like especially to thank our families for their continuous support and encouragement in every our activity and daily life.

University of L'Aquila, 2011 *Andrea De Marcellis*
Giuseppe Ferri

Contents

Introduction

Modern silicon Very Large Scale Integration (*VLSI*) Complementary Metal-Oxide Semiconductor (*CMOS*) technologies can place and interconnect several million transistors on a single Integrated Circuit (*IC*) having sizes approximately lower than 100 mm^2. These integrated technologies have evolved over a long period of time, starting with only few transistors per *IC*, then doubling them about every 18–24 months (according to the well-known Moore's Law), towards the present high densities (about 1–2 billions of transistors, considering recently developed commercial microprocessors). In parallel with the technology evolution, also Computer-Aided Design (*CAD*) and electronic design automation (*EDA*) tools have been developed with the aim to help *IC* designers. Through the use of these tools, design teams have employed very "experienced" designers completely embedded in the same tool management. Therefore, *IC* functionalities, together with the *CAD*/*EDA* tools which guide the design towards the *IC* fabrication, have made available the actual technology to system designers.

All these facilities allow to detect and quantify the bigger part of natural phenomena related to the energy transformation of the parameters, through the use of sensors (i.e., sensing elements), their electronic interfaces and suitable instrumentation and measurement systems.

In fact, recent progresses in physics, chemistry, electronics, material science, bottom/up and top/down technologies have allowed the integration of high performance and low-cost low-size systems, achieving the so-called System-on-Chip (*SoC*), for a variety of applications (i.e., sensor interfacing, signal processing and signal conditioning systems, medical and biological instrumentations, Micro-Electronic-Mechanical System (*MEMS*), etc.). In particular, one of the main aims of actual sensor research is the design of full integrated electronic systems, formed by the sensor, its first analog interface and the processing circuitry, possibly in a miniaturized microelectronic environment (i.e., microsystem). Furthermore, the capability to minimize the sensor element to a nano-scale level and the integration of the sensor itself with the electronic circuit by micromachining and silicon technology, respectively, have opened also new opportunities for electronic interfaces. In this case, a suitable sensor front-end has to be able also to adapt itself to different kinds of both sensors and measurands, through appropriate electronic circuits, and to improve signal processing by apposite circuit design.

Obviously, the first stage of a sensor interface has to be analog, because of the analog nature of the signal coming from sensor. Moreover, analog signal processing offers a high functional density and the capability to directly interface the analog real world of sensors. Furthermore, an Analog-to-Digital (A/D) conversion of the analog output signal is always possible, so as to improve the quality of data display. In this case, owing to the sensor nature, no particular speed constraints are generally necessary; therefore, traditional low-cost and commercial A/D converters can be quite good for a lot of purposes.

Nowadays, fully analog or mixed analog/digital electronic circuits are becoming more and more important for sensors, because the chip-scale integration can be utilized for combining, on the same chip, existing standard *IC* processes, the sensing elements and the processing electronics so to fabricate the so-called smart sensors. This is exalted by the fact that actually the same materials (silicon, polysilicon, aluminium, dielectrics, metal-oxides, etc.) are used to fabricate the majority of sensors, such as, for example, resistive chemical gas sensors based on Metal-Oxide (*MOX*) and silicon-based capacitive pressure sensors, and their front-ends. In this way, standard *CMOS* has been proved to be the main sensor technology, because is able to match the reduction of technological costs with the design of new attractive integrated electronic interface solutions showing low supply voltages and reduced power consumption characteristics.

Starting from these considerations, actually there are basic performances which have to be achieved in *IC* design for the first analog sensor interface: high sensitivity and resolution, high dynamic range, good linearity and high precision, good accuracy, low input noise and offset, long-term temperature stability, reduced silicon area, low effect of parasitic capacitances, calibration and compensation of the transducer characteristics, etc.. These characteristics have to be satisfied by suitable integrated electronic circuits whose typology depends on both the nature of the measurand and the amount of its variation. These interfaces, if designed also with Low Voltage (*LV*) and Low Power (*LP*) characteristics, can be utilized in portable, remote and wireless electronic systems for domestic, industrial, biomedical, automotive and consumer applications, where a great need of reliable and miniature sensor systems has recently grown.

Considering both *LV* and *LP* techniques, the Current-Mode (*CM*) approach, which utilizes the information provided by a current signal instead of voltage as in Voltage-Mode (*VM*), can become, in some cases, a good alternative solution. The main active basic block in *CM* approach is the Second Generation Current Conveyor (*CCII*) which, in different applications, can represent a possible alternative to the traditional Operational Amplifier (*OA*), typically employed in *VM* circuits.

Finally, in the design of a complete integrated sensing system, the capability to operate at environment temperature, as well as at higher temperatures, with also a high linearity, is generally required. This kind of integrated front-end is often formed by a sensor heater (which fixes the employed sensor temperature at a suitable operating point), a proper electronic circuit, converting non-electrical value of the sensing element into a electrical parameter which can be easily utilized by the next stage, and a signal processing unit (typically of digital kind). Therefore, since this complete system sometimes has to be able to reveal a large number of sensing element variation decades, a suitable and accurate design of the analog front-end is mandatory. This is why in this book the main sensor interfacing techniques and front-end circuits, as discrete element prototype boards and, when possible, as integrated architectures, will be described.

Chapter 1
Physical and Chemical Sensors

In this chapter we give an introduction and classification on some examples of physical sensors (devices placed at the input of an instrumentation system that quantitatively measures a physical parameter, for example pressure, displacement or temperature) and chemical sensors (devices which are part of an instrumentation system that determines, typically, the concentration of a chemical substance, such as a toxic gas or oxygen), describing their working principles and main characteristic parameters.

1.1 Sensors and Transducers: Principles, Classifications and Characteristics

The sensor represents the first and main element in measurement and control systems. It is the sensing element, in a revelation equipment, which reacts to the either physical or chemical phenomenon to be detected. It makes use of suitable transduction components so to convert a physical or chemical characteristic into a parameter of different nature, more suitable for the next elaboration through an electronic system. The use of computer-compatible sensors has closely followed the advances in circuit and system design and the advent of the microprocessor. Together with the always-present need for sensors in science and medicine, the demand for sensors in automated manufacturing and processing has rapidly grown. In addition, small and cheap sensors have become important in a large number of consumer products, from children toys to dishwashers and automobiles. Then, the process automation, the fabrication of auto-calibrated devices, the control of the operating condition of a system are only other possible applications of sensors [1–9]. The need of novel sensors and related electronic interfaces showing reduced dimensions and, possibly, *LV LP* characteristics (that is the capability of working with reduced supply voltages and showing a low power consumption) is in a continuous growth since wireless detectors and devices have emerged and moved

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towards commercialization. The possibility for a wide number of devices that give accurate, remote and quick access information about their environment has started to spread. Application areas include health care (verification of the environmental conditions during transport or in storage of diapers, bandages, etc.), food monitoring (food quality during transport, storage and sales) and environmental monitoring (meteorology, road safety, indoor climate, detection of toxic and dangerous gases, etc.). Therefore, one of the important requirements in these researches is the development of *LV LP* and low-cost sensors [10–26]. In particular, the expansion of miniaturized integrated circuits and the advances in microelectronic technologies have made more and more important the design of analog interfaces suitable for the read-out and the processing of signals coming from sensors: in this way, both sensor and electronic circuitry for its interfacing, which have to be developed in a suitable integrated technology (e.g., standard *CMOS*), can be also combined into only one chip, implementing the so-called "Smart Sensor" [27–49].

This Chapter introduces basic definitions and features of sensors, together with some their possible classifications, and illustrates them with some typical examples.

There are many terms which are often used as synonymous for the word "sensor" such as, for an example, transducer, meter, detector, gauge, actuator, etc.. For precision sake, transducers convert signals from an energy domain into signals in a different energy domain. In particular, sensors may be defined as systems which convert signals from non-electrical domains into electrical ones. Actuators are the complementary class of systems which convert electrical signals into non-electrical ones. Concerning transducers, the most widely used definition is that which has been applied to electrical transducers by the Instrument Society of America: *"the transducer is a device which provides a usable output in response to a specified measurand"*. A "usable output" generally refers to an optical, electrical or mechanical signal. In the context of electrical engineering, however, it refers to an electrical output signal. On the other hand, sensors are physical devices which transfer information from different energy domains, such as chemical, optical, mechanical, thermal, magnetic, electrical into an electrical one, providing a broad variety of electrical signals, which are normally of analog kind. In this sense, the "measurand" is defined as the physical, chemical (or biological) property or condition to be measured [1–9].

Sometimes sensors are classified as ***direct*** and ***indirect*** sensors according if one or more than one transduction mechanism is used, respectively. For example, a mercury thermometer is an indirect sensor since it produces a change in volume of mercury in response to a temperature change via thermal expansion, but the output is a mechanical displacement and not an electrical signal, then another transduction mechanism is required. This thermometer is a sensor because humans can read the change in mercury height using their eyes as a second transducing element. On the other hand, in order to produce an electrical output, the height of the mercury has to be converted to an electrical signal; this could be accomplished using a capacitive effect, as an example [1–9].

Fig. 1.1 depicts a simple sensor block diagram identifying the measurand according to the type of input signal and the primary and secondary transduction

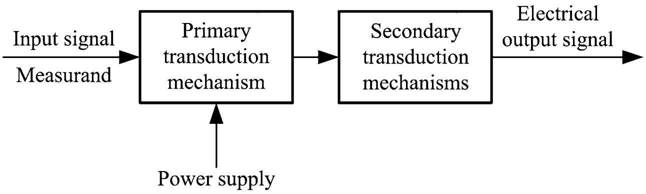

Fig. 1.1 A typical sensor block diagram

mechanisms which give the readable electrical output signal. Classification of sensors can be done according to different approaches. In the following we will show some of these possible points of view [1–9].

In Table 1.1 we report a detailed description of the more commonly employed transduction mechanisms (in particular, primary and secondary signals can be: mechanical, thermal, electrical, magnetic, radiant, chemical, etc.). Many of the effects listed in this Table will be shown in detail in this and next Chapters [1–9].

In order to choose a particular sensor for a given application, there are many factors to be considered. These factors (or specifications) can be divided into two main categories: ***environmental*** factors and ***economic*** factors, as listed in Table 1.2 together with their main characteristics. Most of the environmental factors determine also the packaging of the sensor. The term packaging stands for the encapsulation or insulation which provides protection and isolation and the input/output leads or connections and cabling. The economic factors determine the type of manufacturing and materials used in the sensor and to some extent the quality of the materials (with respect to lifetime). For example, a very expensive sensor may be employed if it is used repeatedly or for very long time periods. On the other hand, a not reusable sensor, often desired in many medical applications, is really inexpensive [1–9].

Another characterization of the sensors regards the type of non-electrical stimulus to be measured; in this sense, we can mention four main families of sensors: sensors for ***mechanical*** phenomenon, sensors for ***hydraulic*** phenomenon, sensors for ***environmental*** phenomenon and sensors for ***electromagnetic*** phenomenon [1–9].

On the other hand, sensors are most often classified simply according to the type of measurand; in particular, there are mainly physical and chemical (or biological) sensors. More in detail:

- ***Physical*** measurands mainly sense temperature, strain, force, pressure, displacement, position, velocity, acceleration, optical radiation, sound, flow rate, humidity, viscosity, electromagnetic fields, etc..
- ***Chemical*** measurands generally detect ion concentration, chemical composition, rate of reactions, reduction-oxidation potentials, gas concentration, etc..

Moreover, with respect to electronic circuits that have to be integrated on the same chip as first analog front-end, sensors are normally divided into two main groups as reported in Table 1.3: ***active*** sensors, which directly produce an output current

Table 1.1 Physical and chemical transduction principles

Primary	Secondary signal					
signal	Mechanical	Thermal	Electrical	Magnetic	Radiant	Chemical
Mechanical	(Fluid) Mechanical and acoustic effects (e.g., diaphragm, gravity balance, echo sounder)	Friction effects (e.g., friction calorimeter); Cooling effects (e.g., thermal flow meters)	Piezoelectricity; Piezoresistivity; Resistive, capacitive and inductive effects	Magneto-mechanical effects (e.g., piezomagnetic effect)	Photoelastic systems (e.g., stress-induced birefringence); Interferometers; Sagnac effect; Doppler effect	–
Thermal	Thermal expansion (bimetal strip, liquid-in-glass and gas thermometers, resonant frequency); Radiometer effect (light mill)	–	Seebeck effect; Thermoresistance; Pyroelectricity; Thermal (Johnson) noise	–	Thermooptical effects (e.g., in liquid crystals); Radiant emission	Reaction activation (e.g., thermal dissociation)
Electrical	Electrokinetic and electromechanical effects (e.g., piezoelectricity, electrometer, Ampere’s law)	Joule (resistive) heating; Peltier effect	Charge collectors; Langmuir probe	Biot-Savart’s law	Electrooptical effects (e.g., Kerr effect); Pockel’s effect; Electroluminescence	Electrolysis; Electromigration
Magnetic	Magnetomechanical effects (e.g., magnetorestriction, magnetometer)	Thermomagnetic effects (e.g., Righi-Leduc effect); Galvanomagnetic effects (e.g., Ettingshausen effect)	Thermomagnetic effects (e.g., Ettingshausen-Nernst effect); Galvanomagnetic effects (e.g., Hall effect, magnetoresistance)	–	Magnetooptical effects (e.g., Faraday effect); Cotton-Mouton effect	–

Radiant	Radiation pressure	Bolometer thermopile	Photoelectric effects (e.g., photovoltaic effect, photoconductive effect)	–	Photorefractive effects; Optical bistability	Photosynthesis; Dissociation
Chemical	Hygrometer; Electrodeposition cell; Photoacoustic effect	Calorimeter; Thermal conductivity cell	Potentiometry; Conductimetry; Amperometry; Volta effect; Flame ionization; Gas-sensitive field effect	Nuclear magnetic resonance	(Emission and absorption) spectroscopy; Chemiluminescence	–

Table 1.2 Main factors in sensor applications

Environmental factors	Economic factors	Sensor characteristics
Temperature range	Cost	Sensitivity
Humidity effects	Availability	Range
Corrosion	Lifetime	Stability
Size		Repeatability
Overrange protection		Linearity
Susceptibility to EM interferences		Error
Ruggedness		Response time
Power consumption		Frequency response
Self-test capability		

Table 1.3 Another possible sensor classification: active and passive sensors and their typical electrical outputs

Main group	Type of sensor	Type of signal	Typical range
Active sensors	Thermopiles, pyroelectric, piezoelectric	Voltage	μV – mV
	Pyroelectric, magnetic	Current	μA – mA
Passive sensors	Humidity, gas, pressure	Capacitance	fF – μF
	Piezoelectric	Charge	fC – pC
	Pressure, chemical, gas	Resistance	kΩ–GΩ

or voltage but require an external power source in order to give a usable output signal, and ***passive*** sensors, which directly modify their internal parameters if an external phenomenon occurs. In the first case, either resistive or capacitive bridges can be interfaced to signal processing and conditioning circuitry such as low noise voltage or current amplifiers. In the second case, the basic parameters of the passive sensors, such as capacitance and resistance, can be measured (according to their variation range) either directly or through some suitable circuits such as oscillators, bridges, charge amplifiers and switched-capacitors based converters [1–10].

Finally, we want to mention that other sensor classifications depend on: how they are fabricated, what is the sensing element, at what physical and/or chemical phenomenon they are able to react, how “electrically” they respond, etc.. In this sense, three main types of sensors will be considered: ***resistive***, ***capacitive*** and ***temperature*** sensors. Since the analog electronic interface especially depends on the kind of sensor and the amount of its variation, this classification seems to be the better and most useful for sensor interface designers, so it will be that mainly adopted in this book.

In the next Paragraphs we will describe firstly the main sensor parameters and then the fundamentals and the working principles of some different kinds of sensors (classifying them with respect to the physical or chemical transduction mechanisms which they show), in a non-exhaustive way. Moreover, in the next Chapters we will present these and other kind of sensors, considering their electrical outputs (type of generated signals by means of different transduction mechanisms), describing also in detail the main analog front-end circuits and interfacing techniques.

1.2 Sensor Main Parameters

In sensor analysis and characterization, it is opportune to evaluate the performances given by the sensor also under different operating conditions. In this sense, the following sensor characteristics can be identified:

- ***static*** characteristics, which describe the performances and the environmental conditions for null or very slow variations of the phenomenon which has to be revealed;
- ***dynamic*** characteristics, which show the performances of a sensor when the phenomenon which has to be detected suffers extensive variations during the observation time;
- ***environmental*** characteristics, which refer to the sensor performances after the exposure (static environmental characteristics) or during the exposure (dynamic environmental characteristics) to specific external conditions (such as temperature, bumps or vibrations).

The main sensor parameters, which have to be considered for evaluating the goodness of a sensor, are the following:

- ***sensitivity***: it is the ratio between the output electrical variation and the input non-electrical parameter variation (measurand variation). It represents the relationship (transfer function) between the output electrical signal and the input non-electrical signal. A sensor will result to be very sensitive when, for the same phenomenon variation to be measured, the electrical signal shows a larger variation. Generally, sensitivity value depends on the operating point of the sensor system, except in the case of direct proportionality between measurand and output value; in this case, it shows a constant value for any working condition.
- ***resolution***: it is the ratio between the output noise level and the sensor sensitivity. It is the minimum detectable non-electrical parameter value under the condition of unitary Signal-to-Noise Ratio (*SNR*). On the other hand, it is defined as the smallest variation of the non-electrical information appreciable from the sensor and which provides a detectable output variation. Least variations of the input non-electrical information below the value of the resolution do not cause valuable variations of output generated signal.

Resolution is definitively the most important sensor characteristic; numerically speaking, it must be minimized. In fact, a system with a very low resolution value is typically mentioned as a "High-Resolution System". Sensitivity and resolution have to be the best possible and must be evaluated in the typical variation range of the non-electrical parameter where, possibly, have to be constant or linear: it means that their value does not depend on the working operating point. These two parameters can be determined also after the interfacing of the "basic" sensor with the first analog front-end that, typically, improves their value [7, 8, 10].

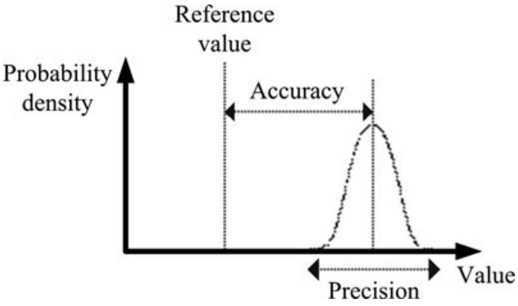

Fig. 1.2 Accuracy and precision definitions and their relationship

Other significant sensor parameters are the following:

- ***Linearity***: proportionality between input and output signals. This parameter is related to the sensor response curve, which correlates the output signal of the sensor to the measurand parameter. Generally, for small measurand variation, linearity is always ensured.
- ***Repeatability***: capability to provide the same performances after a number of utilizations, that is to reproduce output readings for the same value of measurand, when applied consecutively and under the same conditions.
- ***Accuracy***: agreement of the measured values with a standard reference (i.e., ideal characteristic). On the other hand, accuracy is the degree of closeness of a measured or calculated quantity to its reference (expected) value. Accuracy is closely related to precision, also called reproducibility. As a consequence, accuracy is related to percentage relative error between ideal and measured value, as shown in Fig. 1.2.
- ***Precision***: capability to replicate output signals with similar values, for different and repeated measurements, when the same input signal is applied. The precision can be also intended as the degree to which repeated measurements or calculations show the same or similar results. Precision can be considered as the repeatability in the same measurement conditions.
- ***Reproducibility***: it is the repeatability obtained under different measurement conditions (e.g., in different times and/or places).
- ***Stability***: time-invariability of the main sensor characteristics, that is the capability of a sensor to provide the same characteristics over a relatively long period of time.
- ***Hysteresis***: difference among the output signal values, generated by the sensor in correspondence of the same non-electrical input signal range, achieved a first time for increasing values and a second time for decreasing values of the input signal.
- ***Processing speed***: it defines the speed of the generated output signal to reach its final value starting from the instant when the input signal suffers a variation (in this case, a time constant can be also defined).
- ***Noise***: output unwanted signal, produced when the input signal or its variation (to be revealed) is null.

- ***Drift***: it is the (slow and statistically unpredictable) temporal variation of sensor characteristics, due to aging and/or other effects related to sensing materials.
- ***Selectivity***: the presence of different sensitivities to various measurands, sometimes, avoids a useful detection of the sensor answer. Selectivity, or cross-sensitivity, is the capability of the sensor system to maximize only the sensitivity to the desired measurand and to reduce that related to the other chemical or physical parameters that are unavoidably present.

Moreover, output signals coming from sensors, typically, have the following characteristics: low-level values, relatively slow sensing parameter variations and the need of initial calibration for long-term drift (it means they generally can be considered time-variant). For these reasons, in order reduce measuring errors, the use or the design of suitable low-noise low-offset analog interfaces with low parasitic transistors and impedances is essential. In this sense, another important feature to be considered is the electrical impedance of the sensor, which determines the frequency measurement range.

Finally, we want to underline that a sensor is suitable only if all its main parameters are tightly specified for a given range of measurand and time of operation. For example, a highly sensitive device is not useful if its output signal drifts greatly during the measurement time and the data obtained is not reliable if the measurement is not repeatable. Moreover, selectivity and linearity can often be compensated using either additional independent sensor inputs or signal conditioning circuits. In fact, most sensor responses are related to their working temperature, since most transducing effects are temperature-dependent.

1.3 Piezoelectric, Ferroelectric, Electret and Pyroelectric Sensors

The root of the word “piezo” means pressure; hence, the original meaning of the word piezoelectric implied “pressure electricity” (the generation of electric field through an applied pressure). However, this definition ignores the fact that these materials are reversible, allowing the generation of a mechanical movement by applying an electric field. The prefix “ferro” refers to the permanent nature of the electric polarization in analogy with the magnetization in the magnetic case. Even though the root of the word means iron, it does not imply the presence of this material. Then, the “electret” term comes from the words “electrostatic” and “magnet”; in particular, it is formed by “electr”, from “electricity”, and “et”, from “magnet”. An electret material generates internal and external electric fields and is the electrostatic equivalent of a permanent magnet [1–9, 50–67].

Among these sensors, examples of the classes of materials and applications are given in Table 1.4, from which it is evident that many materials exhibit electric phenomena which can be attributed to piezoelectric, ferroelectric and electret

Table 1.4 Electret, ferroelectric, piezoelectric and electrostrictive materials classification

Type	Material class	Example	Applications
Electret	Organic	Waxes	No recent
Electret	Organic	Fluorine based	Microphones
Ferroelectric	Organic	PVF2	No known
Ferroelectric	Organic	Liquid crystals	Displays
Ferroelectric	Ceramic	PZT thin film	NV-memory
Piezoelectric	Organic	PVF2	Transducers
Piezoelectric	Ceramic	PZT	Transducers
Piezoelectric	Ceramic	PLZT	Optical
Piezoelectric	Single crystal	Quartz	Freq. control
Piezoelectric	Single crystal	$LiNbO_3$	SAW devices
Electrostrictive	Ceramic	PMN	Actuators

materials. Here we will discuss the basic concepts in the use of these materials, highlight their applications and describe the constraints that limit their utilization [1–9].

Piezoelectric and ferroelectric materials derive their properties from a combination of structural and electrical properties. As the name implies, both types of materials have electric attributes. A large number of ferroelectric materials are also piezoelectric; however, the contrary is not true. Ferroelectric materials show permanent charge dipoles which arise from asymmetries in the crystal structure. The electric field due to these dipoles can be observed externally to the material when opportune conditions are satisfied (ordered material and absence of charge on the surfaces). Ferroelectrics react to the external fields with a polarization hysteresis and can retain this polarization permanently owing to the thermodynamic equilibrium. Alternatively, some materials consist of large numbers of unit cells; the manifestation of the individual charged groups is, consequently, an internal and an external electric field that arise when the material is stressed. The interaction of an external electric field with a charged group causes a displacement of some atoms in the group, so a macroscopic displacement of the material surfaces. This motion is called piezoelectric effect, that is the conversion of an applied field into a displacement. On the other hand, piezoelectric materials exhibit an external electric field when a stress is applied to it and a charge flow proportional to the strain is observed when a closed circuit is attached to electrodes on the material surface. In ferroelectric materials a crystalline asymmetry exists and allows electric dipoles to form. In symmetrical structures the dipoles are absent and the internal field disappears. All ferroelectric and piezoelectric materials have phase transitions at which the material changes its crystalline symmetry. For example, in these materials there is a change of the symmetry when the temperature is increased. The temperature at which the material spontaneously changes its crystalline phases orsymmetry is called the Curie temperature [1–9].

Electret material is a stable dielectric material that has a permanent electrostatic charge or oriented dipole polarization, which, due to the high resistance of the material, does not decay for hundreds of years. It is similar to ferroelectric one but charges are macroscopically separated and thus are not structural. In some cases, the net charge in the electrets is not zero, for instance when an implantation process is used to embed the charge. Real-charge electrets contain either positive or negative excess charges or both, while oriented-dipole electrets contain oriented dipoles. Moreover, there is a similarity between electrets and the dielectric layer used in capacitors. The difference is that dielectrics in capacitors show an induced polarization that is only transient, dependent on the potential applied on the dielectric, while dielectrics with electret properties exhibit permanent charge storage. Electrets are commonly made by first melting a suitable dielectric material such as a plastic or wax that contains polar molecules and then allowing it to re-solidify in a powerful electrostatic field. The polar molecules of the dielectric align themselves to the direction of the electrostatic field, producing a permanent electrostatic bias. Electret materials are quite common in nature: for example, quartz and other forms of silicon dioxide are naturally occurring electrets, as well as most electrets are made from synthetic polymers (e.g., fluoropolymers, polypropylene, etc.). Although electrets are often characterized as solid (dielectric) materials, a less restrictive view encompasses both solid and liquid systems. Rigid particles or macroscopic surfaces that retain permanent charge or oriented dipoles are rightly termed “solid electrets”, while “liquid electrets,” on the other hand, are formed by inserting charge in the form of electrons, ions, nanometer size micelles or charged colloidal particles into a liquid or onto a liquid-gas or liquid-solid interface. The electret material can be manipulated with external electrostatic fields. With some liquid electrets (e.g., a polymer above its glass transition temperature), unique interface morphologies can be “frozen in” by cooling. The permanent internal or external electric fields, created by electret materials, can be exploited in various applications. Therefore, electrets have recently found commercial and technical interests. For example, they are used in copy machines, microphones, in some types of air filters, for electrostatic collection of dust particles and in ion chambers for measuring ionizing radiation or radon [1–9, 50–53].

As shown in Table 1.4, among these sensors there are three dominant classes of materials: organics, ceramics and single crystals. All these classes have important applications of their piezoelectric properties. In order to exploit the ferroelectric property, recently a strong effort has been devoted to produce thin films of *PZT* (common name for piezoelectric materials of the lead (Pb) zirconate titanate family) on various substrates of silicon-based memory chips for non-volatile storage. In these devices, data is retained without an external power as positive and negative polarization. The polarization is the amount of charge associated with the dipolar or free charge in a ferroelectric or an electret, respectively; it corresponds to the external charge which must be supplied to the material to produce a polarized state from a random state (twice that amount is necessary to reverse the polarization). The statement is rigorously true if all movable charges in the material are reoriented (i.e., saturation can be achieved). Organic materials have not been used for their ferroelectric properties. Liquid crystals in display applications are used for their