Acoustic Wave Sensors

Theory, Design, and Physico-Chemical Applications

D. S. Ballantine, Jr.
Chemistry Department
Northern Illinois University
De Kalb, Illinois

S. J. Martin
A. J. Ricco
G. C. Frye
Microsensor R&D
Sandia National Laboratories
Albuquerque, New Mexico

H. Wohltjen
Microsensor Systems, Inc.
Bowling Green, Kentucky

R. M. White
Department of Electrical Engineering
and Computer Science
Berkeley Sensor & Actuator Center
University of California
Berkeley, California

E. T. Zellers
Department of Environmental
and Industrial Health
Department of Chemistry
University of Michigan
Ann Arbor, Michigan

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Series Preface

Modern Applications of Acoustics is a series, that will, in the hopes of the editors, present the most exciting developments in the applications of acoustics that have emerged in the past few decades. This first seven-author volume, which was already nearing publication when the series was conceived, is an auspicious beginning. It can be argued that all living entities have their own built-in biological acoustic sensors, be they aural or tactile, whose sensitivity, in some instances, is at the optimum signal-to-noise level. For instance, it is known that if the human ear were any more sensitive, Brownian noise would mask the intelligibility of perceived sound. It is possible that the sound emitted by crackling dry leaves and twigs may be the first artificial sensors devised by humans for detecting game or intruders. The sensors described in this volume avail themselves of the most modern microphotolithographic techniques, and use sophisticated signal processing techniques that could not be achieved without the use of the formidable power of modern computers. But, the germinal ideas are the product of human ingenuity.

The editors envision that future volumes will be authored by scientists and engineers who are internationally recognized in their fields as experts and who have made major contributions to the advancement of their areas. The series will include volumes that may be prepared by a single author, a few co-authors, or in the instance of emerging fields, the required expertise may best be harnessed by a guest editor who then will solicit contributions from many experts in narrower subfields.

At present the editors are actively pursuing the publication of volumes in thermoacoustic engines, resonant ultrasonic spectroscopy, modern architectural design, active noise suppression, biological and industrial flow detection, nondestructive evaluation, underwater detection, acoustic tissue characterization, sonoluminescense, and more.

The editors dedicate this series to their thesis advisor and mentor, Professor Isadore Rudnick.

Richard Stern
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Chapter 1 | Why *Acoustic* Sensors?

Precise measurement tools are necessary parts of most successful scientific and engineering enterprises. The sensing devices that we consider in this volume are such tools, capable of measuring physical, chemical, and biological quantities. What they have in common is that they all employ acoustic waves in their operation. The purpose of this introductory chapter is to provide an overview of these devices, and to answer the question: why use *acoustic* sensors?

1.1 What Is a Sensor?

The sensors we consider here produce an output signal in response to some input quantity, as indicated schematically in Figure 1.1(top). The output signal is usually electrical — an analog voltage or current, a stream of digital voltage pulses, or possibly an oscillatory voltage whose frequency represents the value of the input quantity. The range of input quantities covered in this book is large, including physical quantities such as the mechanical properties of thin films, and chemical and biological quantities such as the concentrations and identities of unknown species in air or liquid media.

Inside the typical sensor of Figure 1.1(top), a process of transduction takes place, converting the input event into an electrical signal. The sensor may also contain circuitry that converts the often feeble electrical signal from the transduction process into a more robust form suitable for use outside the sensor itself. The output signal may be stored in a computer memory for later examination. Possible applications would have the signal activating an alarm to warn of the

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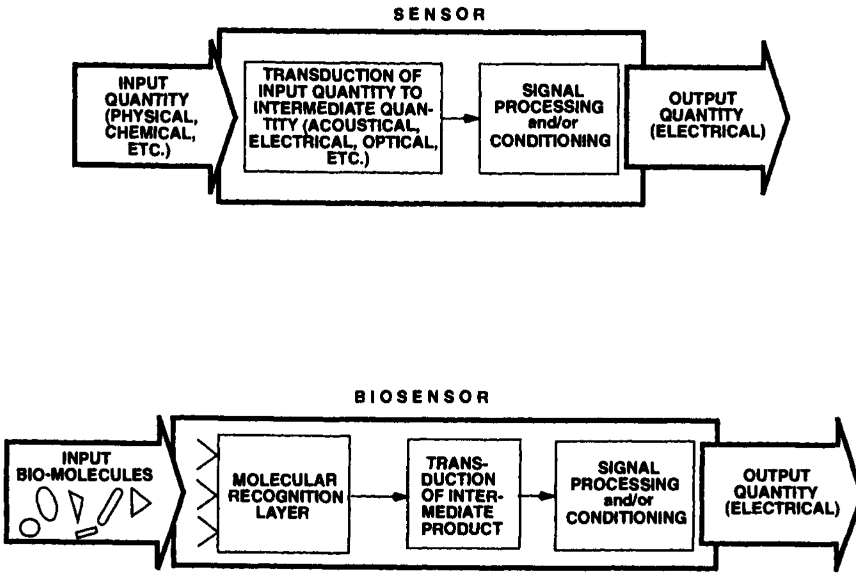

Figure 1.1 Sensor principles. (Top) Schematic diagram of a sensor that produces an electrical output in response to the presence of an input quantity. (Bottom) Biosensor comprising the generic device shown at top with a molecular recognition layer that has a highly selective response.

presence of a toxic vapor, or combining with other signals to provide a physician with information on which to base a medical decision.

Sensors are characterized in many different ways. Their *sensitivity* is a measure of the magnitude of the output signal produced in response to an input quantity of given magnitude; their *resolution* is a measure of the minimum change of input quantity to which they can respond; and their *selectivity* characterizes the degree to which they can distinguish one input quantity from another. However, with chemical sensors for vapors or gases, high selectivity is usually desired but often hard to achieve. A telling example is the commercial Taguchi gas sensor for natural gas or propane, which employs a fairly nonselective solid-state process that takes place at the surface of its heated sensing resistor. When a gas molecule reaches the sensor surface, it can strongly affect the electrical resistance of the element and thus trigger an alarm circuit. According to the manufacturer's instructions, however, the user achieves selectivity by mounting the device high on the wall if natural gas is to be detected, or near the floor if propane sensing is desired — propane being more dense than natural gas!

In contrast, with certain biosensors selectivity can be very high. The biosensor may include as a "front end" a biorecognition element which responds to only one biological substance. As illustrated in Figure 1.1(bottom), the molecular recognition element may contain particular molecules that react with only one other type of molecule. The example in the figure suggests using particular antibodies (the dark cloven objects) that bind to only one type of antigen (the triangularly shaped one). Exploiting this bioselectivity can permit detection of very low concentrations of substances in a very dense background of other molecules.

1.2 The Microsensor Revolution and the Role of Acoustics

The development of integrated circuits reduced the cost of computing, storing, and transmitting information from one location to another. It also made possible very sophisticated yet economical systems to deal with signals from sensors. But until recently, the sensors themselves had not evolved much, and were still fairly large and expensive devices. As an example, a standard device for determining the concentration and identity of unknown vapors was still a heavy, half-meter-long infrared spectrophotometer costing around ten thousand dollars. Sensor development lagged behind that of integrated circuits, and so increasing attention was directed toward the development of inexpensive microsensors.

The success of this effort has resulted in the availability of a growing number of microsensors that are now moving from the research laboratories into development, commercialization, and use [1]. The effort worldwide engages many workers, and resulted in more than three thousand references to "chemical sensors" alone in the period from 1985 through 1989. One thread of this work has been the miniaturization of familiar potentiometric and amperometric chemical sensors [2]. Another is the use of optical sensors in which changes in optical index of refraction, amount of absorbance, or intensity of photoluminescence provide chemical or biological information. Yet another part of the effort has been based on acoustics, or more explicitly, the use of elastic waves at frequencies well above the audible range propagating in specially designed solid sensing structures.

The first of the acoustic sensors was the so-called quartz crystal microbalance (Fig. 1.2a). The "QCM," as it has been known by chemists, employed a slightly modified quartz crystal made initially to stabilize the frequencies of radio transmitters. The modification that permitted it to be used for chemical sensing was the addition of a sorptive film on the crystal. This device was analyzed and improved by a succession of workers starting in the 1950s [3; 4]. Another advance was made in the late 1970s when Wohltjen and Dessy [5] realized that chemical vapor sensing could be accomplished with a device designed originally for processing purely electrical signals, the surface-acoustic-wave delay line (Figure 1.2b). In this device, acoustic waves are generated and detected with the comblike conducting structures shown at each end of the device; a piezoelectric material in the device substrate converts energy between electrical and mechanical forms at the comblike structures. More recently, two other sensors were introduced that employ similar principles but exploit different modes of elastic wave propagation — the acoustic-plate-mode device (Figure 1.2c) and the flexural-plate-wave device (Figure 1.2d).

These devices are conveniently small, relatively inexpensive, quite sensitive, and inherently capable of measuring a wide variety of different input quantities. It is because of these far-reaching characteristics that we have written this book in order to bring a diverse audience of readers an understanding of acoustic sensor principles.

1.3 Where They Fit and How They Are Used

The four types of sensors that we discuss in this book operate over a frequency range of three orders of magnitude — from less than one to more than one-thousand megahertz. In fact, the frequency spectrum of acoustic waves actually extends to more than eighteen orders of magnitude, as indicated by Figure 1.3 (page 6). This range is nearly as large as that commonly shown in charts of the electromagnetic wave spectrum. Incidentally, Figure 1.3 shows that there are many other types of acoustic sensors designed for purposes ranging from imaging the human heart to detecting cracks in airplane parts [6].

All of the sensors of Figure 1.2 "sense" by producing a change in the characteristics of the path over which the acoustic waves travel; the nature of these changes will be discussed in detail in later chapters. As suggested in Figure 1.4 (page 7), there are several ways of detecting such changes. One is the "active" approach in which one makes the sensor a part of an electronic oscillator circuit

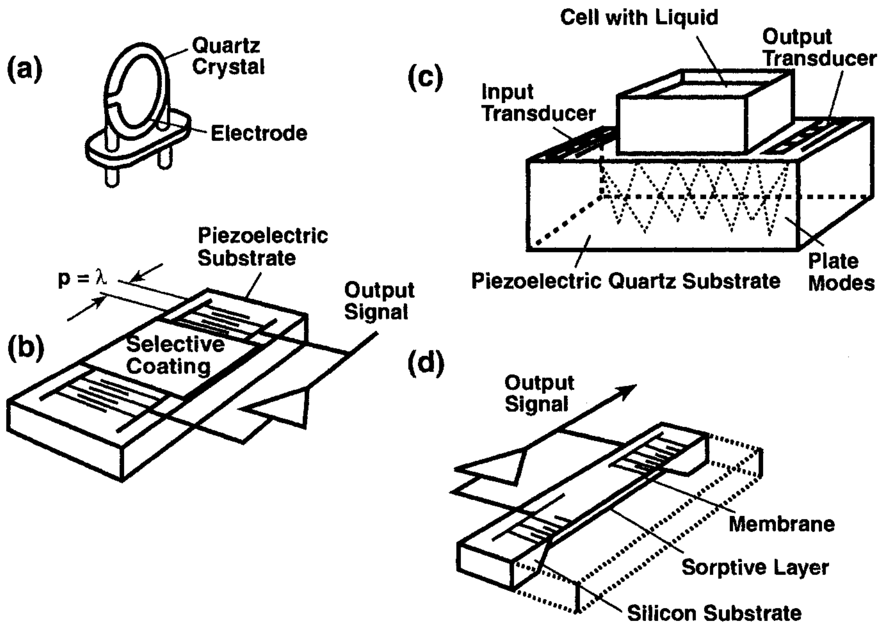

Figure 1.2 Schematic sketches of the four types of acoustic sensors discussed in detail in this book: (a) Resonant quartz crystal like that used in electronic communications systems (after Lu [6]); (b) Surface-acoustic-wave delay line with selective absorptive coating (after Wohltjen and Dessy [5]); (c) Acoustic-plate-mode delay line made from quartz crystal (after Ricco and Martin [7]); (d) Thin-membrane flexural-plate-wave delay line made by microfabrication techniques from a silicon wafer.

so that a change in the characteristics of the acoustic path cause a change in the frequency of the oscillator. This approach is a natural one for the quartz crystal resonator (Figure 1.2a), as the resonator was originally made for use in electronic oscillators. In a typical vapor-sensing application, the sorption of vapor molecules in a polymeric coating applied to one surface of the crystal increases the crystal's mass and lowers its resonant frequency and that of the circuit in which it is installed. The active approach is also illustrated with the surface-acoustic-wave and the flexural-plate-wave devices in Figures 1.2b and 1.2d, where electronic amplifiers are shown connected between input and output transducers of the devices.

The alternative approach for getting information from these acoustic sensors is to measure the sensor characteristics passively; that is, to supply an external

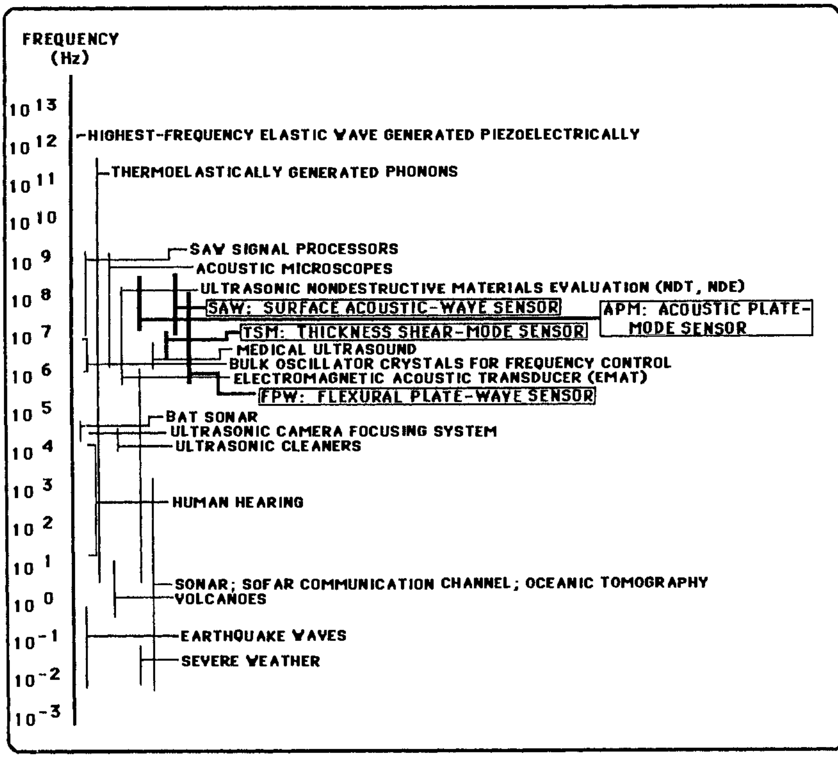

Figure 1.3 Acoustic-wave spectrum. Almost as broad as the familiar electromagnetic-wave spectrum, the spectrum of acoustic waves that have been excited or detected covers frequencies that range over roughly eighteen orders of magnitude. The four sensors on which we concentrate, indicated by bold lines, range in operation from below 1 MHz to slightly above 1000 MHz.

electrical test signal and determine the response of the sensor to that signal. For example, as shown in later chapters, by measuring the attenuation of the test signal we can determine the viscosity of a fluid that contacts one of these sensors. In the following chapters we discuss these measurement options thoroughly.

The most commercially developed of the acoustic sensors we will discuss is the quartz-crystal microbalance. This device is often used in vacuum deposition systems where it measures the thickness of deposited coatings. The commercial sensor shown in Figure 1.5 (page 8) includes a vacuum-tight water cooling system and a microprocessor-based controller that can be set for measuring and indicating the deposition rate and total thickness of films having different densities and sound speeds. Incidentally, hereafter we will refer to this device by the

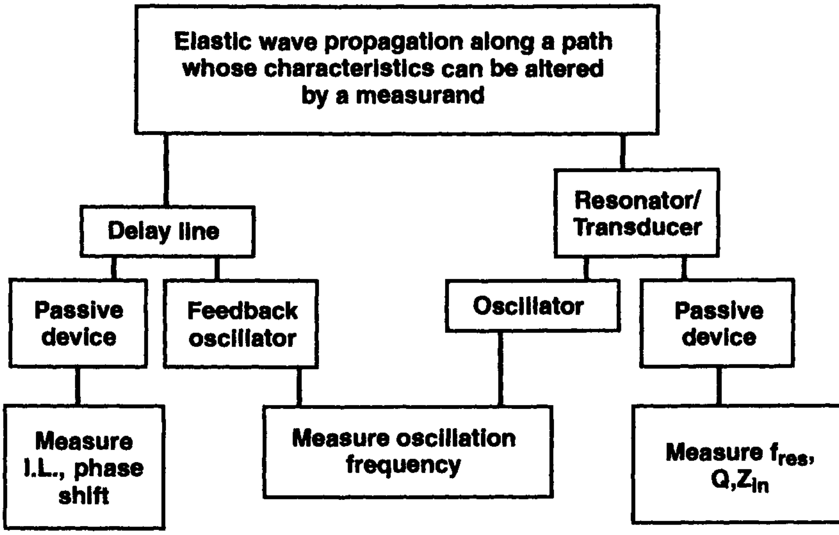

Figure 1.4 Measurement schemes used with the acoustic sensors illustrated in Figure 1.2. I.L. = insertion loss, f_{res} = resonant frequency, Q = quality factor, and Z_{in} = input impedance.

more generic name "thickness-shear-mode" (TSM) sensor, since that name emphasizes the mode of propagation instead of the material from which the device is made.

The surface-acoustic-wave sensor is also commercially available, either as a single sensor or as a part of an entire sensing system. The authors hope that informing potential users about acoustic sensors may stimulate the wider use of all the sensors that we discuss.

1.4 About the Authors and the Rest of the Book

It will be clear upon skimming through this book that we are dealing with a multidisciplinary subject. The disciplines involved include acoustics, electrical circuits, chemistry, some biology, and a lot of materials science and engineering. In view of this diversity, we have tried to provide plenty of supportive background material.

The same multidisciplinary mix characterizes the authors: some are chemists (Ballantine, Ricco, Wohltjen, and Zellers); one is an electrical engineer (Martin);