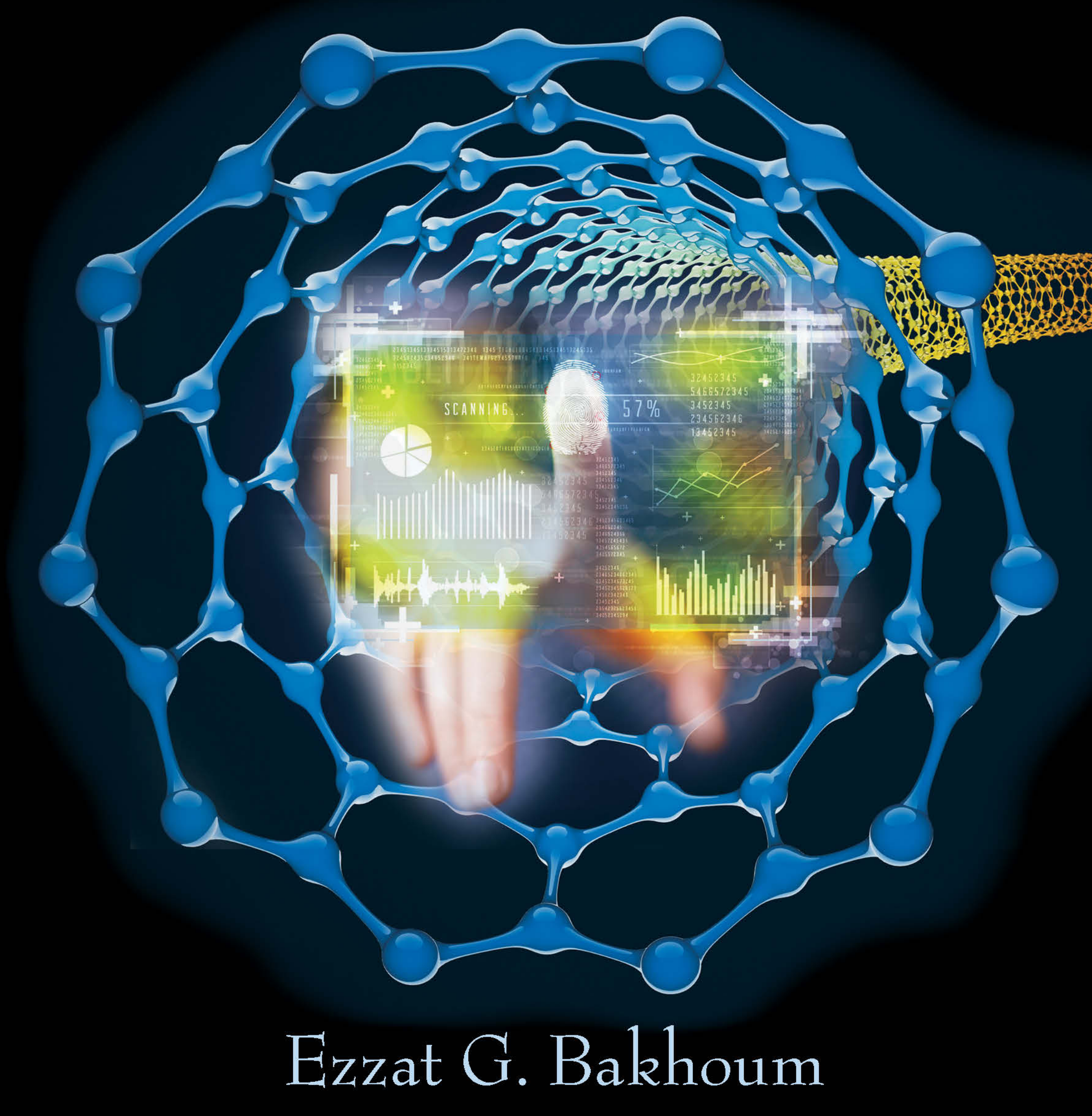
Micro- and Nano-Scale Sensors and Transducers



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Preface

The past decade has witnessed substantial advances in sensor technology. The emerging new field of nanotechnology and nanofabrication has allowed the creation of a new array of sensors and transducers with remarkable properties. Pressure sensors, gas sensors, optical sensors, biological sensors, etc., have all seen dramatic improvements in characteristics such as sensitivity and dynamic range, in addition to substantial miniaturization. This book presents a summary of the state of the art of sensor and transducer technology as of 2014. Although a very large number of books on nanotechnology in general currently exist in the marketplace, recent advances in micro- and nano-scale sensors and transducers are not adequately represented in the literature. This book attempts to fill that gap. The intended audience for this book is practicing industry engineers, corporate and government researchers, and graduate students in electrical engineering, mechanical engineering, and physics.

The main topics covered in the book are the following:

- Pressure Sensors (Chapter 1): The first chapter presents the novel new structures of pressure sensors, used extensively in such applications as mechanical pressure sensing, gas pressure sensing, atmospheric pressure sensing, etc. Pressure sensors that are based on capacitance variation, in particular, have benefited from the recent advances in nanotechnology and nanofabrication, and this type of pressure sensor is covered extensively.

- Motion and Acceleration Sensors (Chapter 2): Motion and acceleration sensors are used in many applications, from automobile air bags to projectiles to smart tablets and cell phones. This category of sensors has also benefited greatly from the nanotechnology/nanofabrication revolution. The novel structures of the new motion and acceleration sensors that appeared recently in archival publications along with their amazing characteristics are presented in Chapter 2.

- Gas and Smoke Sensors (Chapter 3): Highly sensitive and miniature gas and smoke sensors that are based on nanostructured electrodes have been introduced recently in the literature. Chapter 3 describes these sensors.

- Moisture Sensors (Chapter 4): Novel new techniques based on nanotechnology for detecting atmospheric moisture as well as moisture inside small electronic components have also appeared in the literature recently. Although not yet available commercially, these anticipated new sensors are ultraminiature in size yet ultrasensitive. Chapter 4 introduces these sensors.
- Optoelectronic and Photonic Sensors (Chapter 5): Nanotechnology has revolutionized a number of classical applications by allowing the integration of optical sensing techniques into such applications. Advanced new products in this category include optical microphones, fingerprint readers, and highly sensitive seismic sensors. These advanced new applications are covered in Chapter 5.
- Biological Sensors, Chemical Sensors, and the so-called "Lab-on-a-Chip" (Chapter 6): Another important revolution based on nanotechnology has culminated in multipurpose biological and chemical analysis devices where each device is fully contained in one integrated circuit (the so-called Lab-on-a-Chip) in addition to other advanced chemical and biological sensors. A survey of these sensors is given in Chapter 6.
- Electric, Magnetic, and RF/Microwave Sensors (Chapter 7): Enormous advances in electric field, magnetic field, and RF/Microwave sensors, driven by nanotechnology, have occurred recently. A description of these sensors, along with their applications, is given in Chapter 7.
- Integrated Sensor/Actuator Units and Special Purpose Sensors (Chapter 8): The last chapter of the book is dedicated to integrated sensor/actuator units and special-purpose sensors. New devices that benefited from nanotechnology, such as new icing detectors for aircraft, new microfluidic sensor/actuator units for microrobots and inkjet printers, etc., are described in Chapter 8.

With the information provided in this book, the corporate researcher or design engineer will be able to:

- understand the differences between the new sensor and transducer technology (which is mainly based on nanotechnology and nanofabrication) and the older or "classical" sensor technologies;
- make an informed selection of a sensor or transducer for a particular application;
- become knowledgeable about the technologies that are available commercially at the present time and the technologies that are anticipated to become available within a time span of a few months to a few years.

Each chapter of the book ends with a set of quizzes/short questions, along with answers.

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Chapter 1

Pressure Sensors

1.1 Capacitive Pressure Sensors

Among the pressure sensors that are widely used in the industry, capacitive pressure sensors are particularly noteworthy. These sensors are characterized by very low temperature hysteresis and pressure hysteresis, in addition to low power consumption [1–8]. Traditional capacitive pressure sensors, however, suffer from inherently poor resolution (a typical capacitive pressure sensor offers a total change in capacitance of only a few pico-farads, which usually necessitates the use of a sophisticated interface/compensation circuit to sense the very small variations in capacitance). New capacitive pressure sensors with extremely high resolution and sensitivity, based on nanotechnology, were introduced recently [9]. This section introduces the mercury droplet capacitive pressure sensor, the sensor with the highest reported sensitivity and resolution. This type of sensor is currently in production and should be commercially available in early 2015.

1.1.1 Structure

The recently introduced mercury-droplet capacitive pressure sensor has demonstrated a change in capacitance of approximately 6.73 μF over a pressure range of 0 to 3 kPa. The sensitivity of this type of sensor is therefore 2.24 μF/kPa, substantially higher than any of the known types of capacitive pressure sensors. The basic concept of the new sensor is to mechanically deform a drop of mercury that is separated from a flat aluminum electrode by a very thin layer of a dielectric material, so as to form a parallel-plate capacitor where the electrode area is variable to a high degree. This principle is illustrated in Figure 1.1 below.

The principle of the new device, therefore, is to create a capacitor with a variable electrode area, rather than a variable interelectrode spacing as commonly done in the

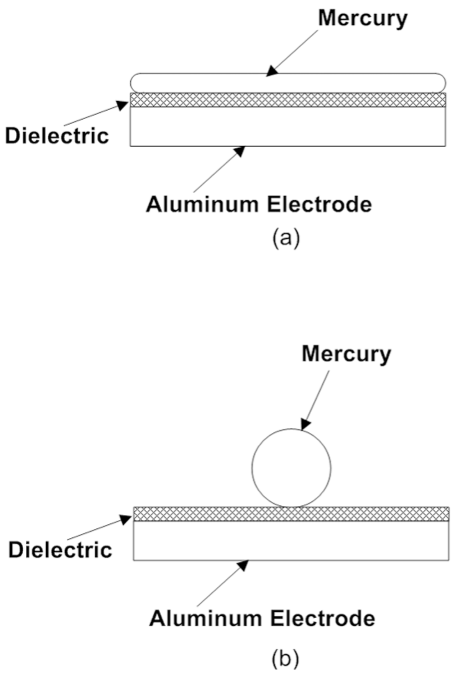

Figure 1.1: (a) A drop of mercury is flattened against an aluminum electrode that is covered with a layer of a dielectric material. A parallel-plate capacitor with one liquid electrode is formed. (b) Under zero pressure, the mercury drop returns to its nearly spherical shape. The change in capacitance between the two configurations (which is proportional to the change in the contact area of the liquid electrode) can be several hundred fold.

devices shown in the literature. The detailed structure of the new sensor, together with the test data, is given in the following sections. Table 1.1 below lists the four most important parameters of the new sensor: sensitivity, linearity, pressure hysteresis, and temperature hysteresis, as compared to the other known types of pressure sensors.

As the table shows, the sensitivity of the new sensor is substantially higher than any of the known types of pressure sensors. The hysteresis error is also substantially lower than that of other sensors. The drawback, however, is that the maximum temperature-related error is slightly worse than that of the other capacitive pressure sensors (due to the thermal expansion of the mercury droplet, particularly at high temperatures), although it is still better than the temperature-related error offered by piezoresistive sensors. Another important fact to mention is that while the sensor is nonlinear (like most other capacitive sensors), the equation that relates the capacitance to the applied pressure is exactly known, as will be demonstrated in the following sections.

The basic structure of the new sensor is shown in Figure 1.2. A drop of mercury of a 3 mm diameter is placed on top of a flat aluminum electrode that is covered with a

Table 1.1 Comparison of the new sensor to the two most important types of pressure sensors: Capacitive and piezo-resistive (see [10–14]).

	Sensitivity	Linearity	Pressure Hysteresis	Temperature Hysteresis (For temp. range of −10°C to +80°C)
Piezoresistive pressure sensors	Up to 25 mv/kPa	Generally linear	Up to ± 1% FSO	Up to ± 2% FSO
Capacitive pressure sensors	Up to 0.2 nF/kPa	Generally nonlinear	Up to ± 0.1% FSO	Up to ± 0.5% FSO
New sensor (uncompensated)	2.24 μF/kPa	Nonlinear	Less than ± 0.05% FSO	Up to ± 1.5% FSO

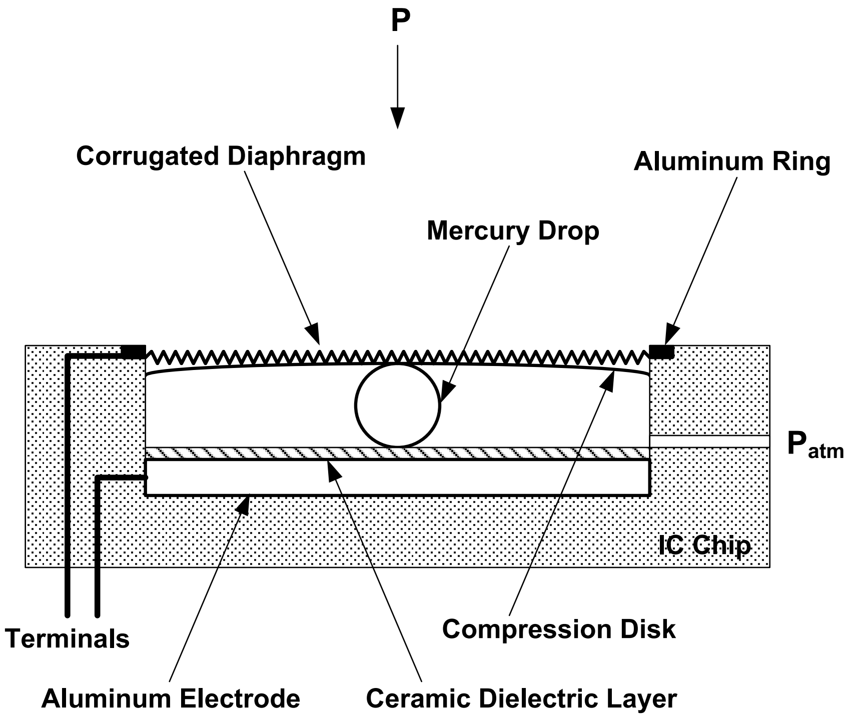

Figure 1.2: Mechanical structure of the sensor.

1 μm thick layer of a ceramic material that has a very high dielectric constant (specifically, $BaSrTiO_3$, with a dielectric constant of 12,000–15,000). The drop is held in place by means of an aluminum disk that serves as the compression mechanism. The compression disk, in turn, is acted upon by means of a corrugated stainless steel diaphragm, as shown (those corrugated diaphragms are available from a number of industrial suppliers). The compression disk is given a slight curvature, as shown in the figure, such that the spacing between the disk and the ceramic layer is exactly 3 mm at the center, but less than 3 mm everywhere else. In this manner, the mercury drop will be forced to the center each time the stainless steel diaphragm retracts. The diaphragm is held in place by means of a thin aluminum ring, as shown (conductive paste between the rim of the diaphragm and the ring allows an air-tight seal to be formed). The entire assembly is mounted inside an open-cavity, 24-pin DIP IC package. A photograph of the components of the sensor is shown in Figure 1.3.

Since the air that surrounds the mercury droplet must be allowed to exit from the sensor and re-enter as the sensor is pressurized/depressurized, an atmospheric pressure relief conduit is drilled in the IC package, as shown on the right hand side of Figure 1.2. In most applications, that conduit will be connected to an atmospheric pressure environment via, for example, an external tube to be connected to the sensor

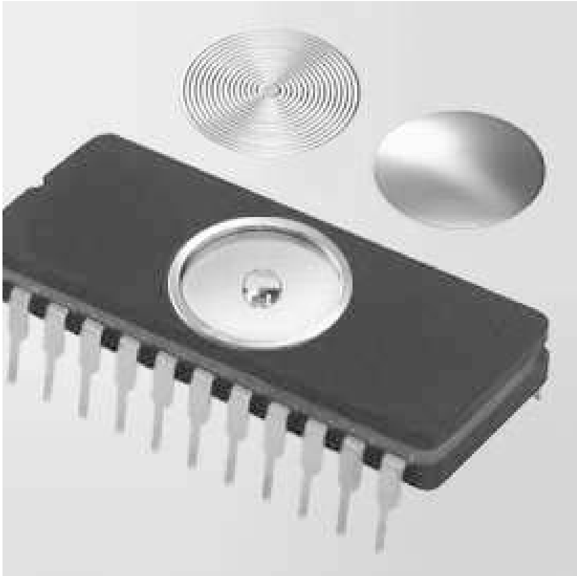

Figure 1.3: Components of the sensor. The sensor is totally mounted inside a standard 24-pin DIP IC package (dimensions: 30 mm $\times$ 14 mm).

(it will be advantageous to connect the pressure relief conduit to the ambient environment through a moisture isolation chamber, in order to prevent moisture from penetrating inside the sensor). In applications where it is desired to detect pressures that are lower than the atmospheric pressure at sea level (like aircraft altitude applications, for example), then a suitable vacuum can be initially applied to the pressure relief conduit (in which case the mercury drop will be initially flattened at sea level).

Concerning the 1 μm thick layer of $BaSrTiO_3$, it is deposited on the surface of the aluminum electrode by using the electrophoretic deposition technique [15]. Figure 1.4 shows a scanning electron microscope (SEM) picture of the ceramic layer deposited on the surface of the electrode. The dielectric constant of the ceramic layer was found to be approximately 12,000, as expected for this material [16, 17].

A word is now in order concerning the interface circuit used with the sensor. At the present time, the interface circuit used is a 555 timer working in an oscillator mode, essentially for converting the capacitance to frequency. Such a circuit is very well known in the literature and is described in references such as [18]. The equation that characterizes the 555 oscillator is $(1 - \exp[-1/2fRC]) = 2/3$ [18]. Given a known resistance R, the value of the unknown capacitance C can be easily calculated from that equation by observing the frequency f of the resulting square wave. The miniature, surface-mount 555 chip is integrated inside the open cavity package shown in Figure 1.3 (the chip is mounted underneath the sensor and is not shown in the photograph). It is to be pointed out that the interface circuit does not amplify or