Chapter 78
Multisensor Smart System on a Chip

Louiza Sellami and Robert W. Newcomb

Abstract Sensors are becoming of considerable importance in several areas, particularly in health care. Therefore, the development of inexpensive and miniaturized sensors that are highly selective and sensitive, and for which control and analysis is present all on one chip is very desirable. These types of sensors can be implemented with microelectromechanical systems (MEMS), and because they are fabricated on a semiconductor substrate, additional signal processing circuitry can easily be integrated into the chip, thereby readily providing additional functions, such as multiplexing and analog-to-digital conversion. Here, we present a general framework for the design of a multisensor system on a chip, which includes intelligent signal processing, as well as a built-in self-test and parameter adjustment units. Specifically, we outline the system architecture and develop a transistorized bridge biosensor for monitoring changes in the dielectric constant of a fluid, which could be used for in-home monitoring of kidney function of patients with renal failure.

Keywords Fluid Biosensors · MEMS · Sensors · Smart systems · System on a chip

78.1 Introduction

In a number of areas, it would be useful to have available smart sensors which can determine the properties of a fluid and from those make a reasoned decision. Among such areas of interest might be ecology, food processing, and health care. For example, in ecology, it is important to preserve the quality of water for which a number of parameters are of importance, including physical properties such as

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color, odor, pH, as well as up to 40 inorganic chemical properties and numerous organic ones [1, pp. 363–366]. Therefore, to determine the quality of water, it would be extremely useful if there were a single system on a chip which could be used in the field to measure the large number of parameters of importance and make a judgment as to the safety of the water. For such, a large number of sensors are needed and a means of coordinating the readouts of the sensors into a user-friendly output from which human decisions could be made. As another example, the food processing industry needs sensors to tell if various standards of safety are met. In this case, it is important to measure the various properties of the food, for example, the viscosity and thermal conductivity of cream or olive oil [2, pp. 283–287].

In biomedical engineering, biosensors are becoming of considerable importance. General theories of different types of biosensors can be found in [3–5] while similar devices dependent upon temperature sensing are introduced in [6]. Methods for the selective determination of compounds in fluids – such as blood, urine, and saliva – are indeed very important in clinical analysis. Present methods often require a long reaction time and involve complicated and delicate procedures. One valuable application in the health care area is that of the use of multiple sensors for maintaining the health of astronauts where presently an array of 11 sensors is used to maintain the quality of recycled air [7], although separate control is effected by the use of an external computer. Therefore, it is desirable to develop inexpensive and miniaturized sensors that are highly selective and sensitive, and for which control and analysis is available all on the same chip. These sensors can be implemented with microelectromechanical systems (MEMS). Since they are fabricated on a semiconductor substrate, additional signal processing units can easily be integrated into the chip, thereby readily providing functions such as multiplexing and analog-to-digital conversion. In numerous other areas, one could find similar uses for a smart multisensor array from which easy measurements can be made with a small portable device. These are the types of systems on a chip (SOC) that this chapter addresses.

78.2 System on a Chip Architecture

The architecture of these systems is given in Fig. 78.1 where there are multiple inputs, sensors, and outputs. In between are smart signal processing elements including built-in self-test (BIST). In this system, there may be many classes of input signals [e.g., material (as a fluid) and user (as indicator of what to measure)]. On each of the inputs, there may be many sensors [e.g., one material may go to several sensors each of which senses a different property (as dielectric constant in one and resistivity in another)]. The sensor signals are treated as an N-vector and combined as necessary to obtain the desired outputs, of which there may be many (such as an alarm for danger and indicators for different properties). For example, a patient with kidney disease may desire a system on a chip which gives an indication of when to report to the hospital. For this, an indication of deviation of dielectric

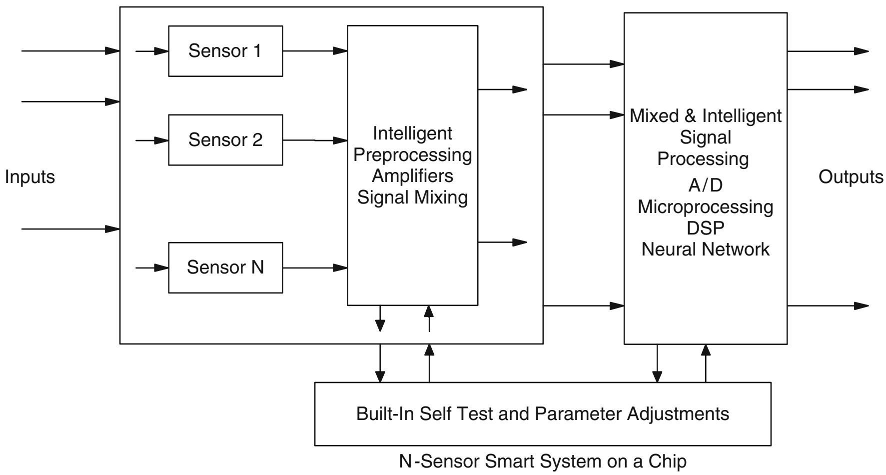

Fig. 78.1 Architecture for *N*-sensor smart system on a chip

constant from normal and spectral properties of peritoneal fluid may be sensed and combined to give the presence of creatinine (a protein produced by the muscles and released in the blood) in the fluid, with the signal output being the percent of creatinine in the fluid and an alarm when at a dangerous level.

78.3 Dielectric Constant and Resistivity Sensor

The fluid sensing transistor in this sensor can be considered as a VLSI adaptation of the CHEMFET [7, p. 494] which we embed in a bridge to allow for adjustment to a null [8]. The sensor is designed for ease of fabrication in standard VLSI processing with an added glass etch step. A bridge is used such that a balance can be set up for a normal dielectric constant, with the unbalance in the presence of a body fluid being used to monitor the degree of change from the normal. The design chosen leads to a relatively sensitive system, for which on-chip or off-chip balance detection can occur. In the following, we present the basic sensor bridge circuit, its layout with a cross section to show how the chip is cut to allow measurements on the fluid, and simulation results from the Spice extraction of the layout that indicate the practicality of the concept.

Figure 78.2 shows a schematic of the sensor circuit. This is a capacitive-type bridge formed from four CMOS transistors, the two upper ones being diode-connected PMOS and the two lower NMOS, one diode connected and the other with a gate voltage control. The output is taken between the junction of the PMOS and NMOS transistors, and as such is the voltage across the midpoint with the circuit being supplied by the bias supply. As the two upper and the lower right transistors are diode connected, they operate in the saturation region while the gate

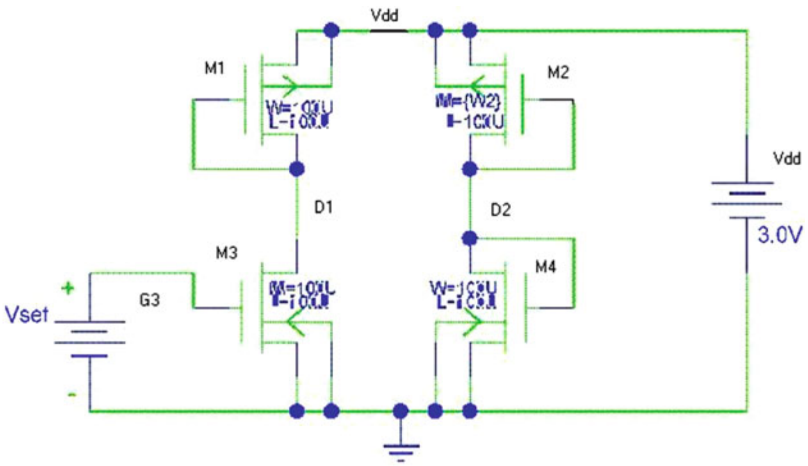

Fig. 78.2 Circuit schematic of a fluid biosensor

(the set node) of the lower left transistor, M_3, is fed by a variable DC supply allowing that transistor to be adjusted to bring the bridge into balance. The upper right transistor, M_2, has cuts in its gate to allow fluid to enter between the silicon substrate and the polysilicon gate. In so doing the fluid acts as the gate dielectric for that transistor. Because the dielectric constants of most fluids are a fraction of that of silicon dioxide, the fraction for water being about 1/4, M_2 is actually constructed out of several transistors, four in the case of water, with all of their terminals (source, gate, drain) in parallel to effectively multiply the Spice gain constant parameter *KP* which is proportional to the dielectric constant.

The sensor relies upon etching out much of the silicon dioxide gate dielectric. This can be accomplished by opening holes in protective layers by using the overglass cut available in MEMS fabrications. Since, in the MOSIS processing that is readily available, these cuts should be over an *n*-well, the transistor in which the fluid is placed is chosen as a PMOS one. And, since we desire to maintain a gate, only portions are cut open so that a silicon dioxide etch can be used to clear out portions of the gate oxide, leaving the remaining portions for mechanical support. To assist the mechanical support, we also add two layers of metal, metal-1 and metal-2, over the polysilicon gate.

A preliminary layout of the basic sensor is shown in Fig. 78.3 for M_2 constructed from four subtransistors, this layout having been obtained using the MAGIC layout program. As the latter can be used with different λ values to allow for different technology sizes, this layout can be used for different technologies and thus should be suitable for fabrications presently supported by MOSIS. Associated with Fig. 78.3 is Fig. 78.4 where a cross section is shown cut through the upper two transistors in the location seen on the upper half of the figure. The section shows that the material over the holes in the gate is completely cut away, so that an etch of

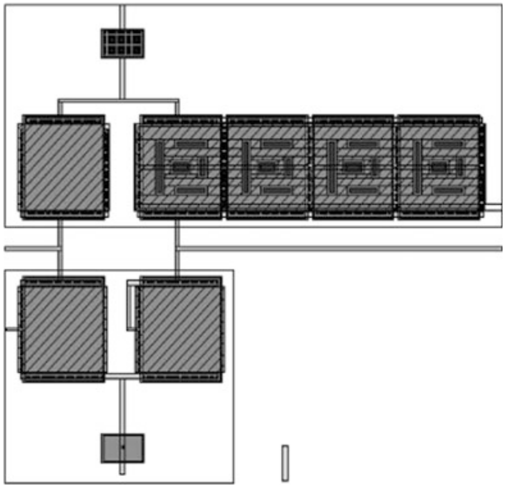

Fig. 78.3 Biosensor VLSI layout

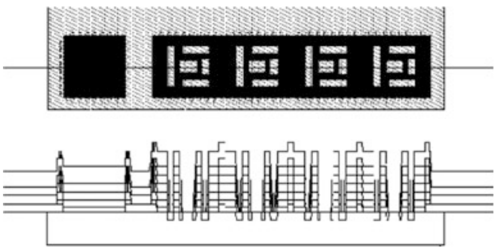

Fig. 78.4 Cross section of upper transistors

the silicon dioxide can proceed to cut horizontally under the remaining portions of the gate. The two layers of metal can also be seen as adding mechanical support to maintain the cantilevered portions of the gate remaining after the silicon dioxide etch.

To study the operation of the sensor, we turn to the describing equations. Under the valid assumption that no current is externally drawn from the sensor, the drain currents of M_1 and M_3 are equal and opposite, $I_{D3} = -I_{D1}$, and similarly for M_2 and M_4, $I_{D4} = -I_{D2}$. Assuming that all transistors are operating above threshold, since M_1, M_3, and M_4 are in saturation they follow a square law relationship while the law for M_3 we designate through a function $f(V_{set}, V_{D1})$ which is controlled by V_{set}. Thus,

$$-I_{D1} = \beta_1 (V_{dd} - V_{D1} - |V_{thp}|)^2 (1 + \lambda_p [V_{dd} - V_{D2}]), \tag{78.1a}$$

$$-I_{D1} = \beta_3 [f(V_{set}, V_{D1})(1 + \lambda_n V_{D1}) = I_{D3}, \tag{78.1b}$$

$$-I_{D2} = \varepsilon\beta_2(V_{dd} - V_{D2} - |V_{thp}|)^2(1 + \lambda_p[V_{dd} - V_{D2}]), \tag{78.2a}$$

$$-I_{D2} = \beta_4(V_{D2} - V_{thn})^2(1 + \lambda_n V_{D2}) = I_{D4}, \tag{78.2b}$$

where, for the ith transistor,

$$\beta_i = KP_i W_i/2L_i, \quad i = 1, 2, 3, 4 \tag{78.3}$$

and

$$f(x, y) = \{(x - V_{thn})^2 \text{ if } x - V_{thn} < y, 2(x - V_{thn})y - y^2 \text{ if } x - V_{thn} \geq y\}. \tag{78.4}$$

Here, V_{th}, KP, and λ are Spice parameters for silicon transistors, all constants in this case, with the n or p denoting the NMOS or PMOS case, and ε is the ratio of the dielectric constant of the fluid to that of silicon dioxide:

$$\varepsilon = \varepsilon_{fluid}/\varepsilon_{SiO_2}. \tag{78.5}$$

To keep the threshold voltages constant, we have tied the source nodes to the bulk material in the layout. In our layout, we also choose the widths and lengths of M_1, M_3, and M_4 to be all equal to 100 μm and L_2/W_2 to approximate ε. Under the reasonable assumption that the λs are negligibly small, an analytic solution for the necessary V_{set} to obtain a balance can be obtained. When M_3 is in saturation, the solution is

$$V_{D1} = V_{dd} - |V_{thp}| - (\beta_3/\beta_1\}^{1/2}(V_{set} - V_{thn}) \tag{78.6}$$

while irrespective of the state of M_3

$$V_{D2} = \{V_{thn} + (\varepsilon\beta_2/\beta_4)^{1/2}(V_{dd} - |V_{thp}|)/[1 + \varepsilon\beta_2/\beta_4]^{1/2}\}. \tag{78.7}$$

Balance is obtained by setting $V_{D1} = V_{D2}$. Still assuming that M_3 is in saturation, the value of V_{set} needed to obtain balance is obtained from (78.6) and (78.7) as

$$V_{set} = V_{thn} + \{(\beta_1/\beta_3)\}^{1/2}(V_{dd} - |V_{thp}| - V_{thn})/[1 + (\varepsilon\beta_2/\beta_4)^{1/2}]. \tag{78.8}$$

At this point, we can check the condition for M_3 to be in saturation, this being that $V_{DS} \geq V_{GS} - V_{thn}$; since $V_{DS} = V_{D1}$ and $V_{GS} = V_{set}$, the use of (78.6) gives

$$V_{thn} < V_{set\{sat\}} \leq V_{thn} + (V_{dd} - |V_{thp}|)/[1 + (\beta_3/\beta_1)^{1/2}]. \tag{78.9}$$

Substituting the value of V_{set} at balance (78.8) shows that the condition for M_3 to be in saturation at balance is $\varepsilon\beta_2 \geq \beta_3$; this normally would be satisfied but can be guaranteed by making M_2 large enough.

Several things are added to the sensor itself per Fig. 78.1. Among these are a differential pair for direct current mode readout followed by a current mode pulse-coded neural network to do smart preprocessing to insure the integrity of the signals. Finally, a built-in test circuit is included to detect any breakdown in the sensor operation.

The sensor is sensitive to the dielectric constant of a fluid over an 11–1 range of dielectric constant most likely can be incorporated into a multisensor chip. Using standard analog VLSI–MEMS processing, one can use the bridge for anomalies in a fluid by obtaining V_{set} for the normal situation and then comparing with V_{set} found for the anomalous situation. This could be particularly useful for determining progress of various diseases. For example, one way to determine kidney function and dialysis adequacy is through the clearance test of creatinine. The latter tests for the amount of blood that is cleared of creatinine per time period, which is usually expressed in ml/min. For a healthy adult, the creatinine clearance is 120 ml/min. A renal adult patient will need dialysis because symptoms of kidney failure appear at a clearance of less than 10 ml/min. Creatinine clearance is measured by urine collection, usually 12 or 24 h. Therefore, a possible use for the proposed sensor could be as a creatinine biosensor device for individual patient to monitor the creatinine level at home. An alternate to the proposed biosensor is based on biologically sensitive coatings, often enzymes, which could be used on M_2 transistor in a technology that is used for urea biosensors which are presently marketed for end stage renal disease patients [4]. The advantage of the sensor presented here is that it should be able to be used repetitively whereas enzyme-based coatings have a relatively short life. The same philosophy of a balanced bridge constructed in standard VLSI processing can be carried over to the measurement of resistivity of a fluid. In this case, the bridge will be constructed of three VLSI resistors with the fourth arm having a fluid channel in which the conductance of the fluid is measured.

78.4 Built-In Self-Test (BIST)

The BIST can interface with the sensors and other circuits under consideration. It can be built upon modifications of circuits and ideas available in the literature, such as the use of oscillations for mixed signal testing including the production line technique of using standard ring oscillator properties. The BIST is needed due to the fact that there are many interacting subsystems, and an error in one can perhaps drastically affect the operation of others.

BIST circuitry consists of a controller, a pattern generator, and a multiple input signature analyzer. The BIST method allows core testing to be realized by commanding the core BIST controller to initiate self-test and by knowing what the correct result should be. On-chip testing of embedded memories can be realized either by multiplexing their address and data lines to external SOC I/O pads or by using the core processor to apply enough read/write patterns of various types to ensure the integrity of the memory. This technique works best for small embedded memories. Some recommend providing embedded memories with their own BIST circuitry.

For BIST to be effective, there must be a means for on-chip test response measurement, on-chip test control for digital and analog test, and I/O isolation. There are three categories of measurements that can be distinguished: DC static measurements, AC dynamic measurements, and time domain measurements. The first of these, DC static measurements, includes the determination of the DC operating points, bias and DC offset voltages, and DC gain. DC faults can be detected by a single set of steady-state inputs. AC dynamic measurements measure the frequency response of the system under test. The input stimulus is usually a sine-wave form with variable frequency. Digital signal processing (DSP) techniques can be employed to perform harmonic spectral analysis. Time domain measurements derive slew rate, rise and delay times using pulse signals, ramps or triangular waveforms as the input stimuli of the circuit.

78.5 Summary

In this chapter, we developed a general framework for the design and fabrication of a multisensor system on a chip, which includes intelligent signal processing, as well as a built-in self-test and parameter adjustment units. Further, we outlined its architecture, and developed a transistorized bridge fluid biosensor for monitoring changes in the dielectric constant of a fluid, which could be of use for in-home monitoring of kidney function of patients with renal failure.

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