# Behavioral Modeling of a Humidity Sensor using an Analog Hardware Description Language

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## ABSTRACT

Measuring relative humidity in breath is useful for diagnosing pulmonary diseases. Humidity capacitive sensors were developed to equip a portable clinical device. Simulation is needed to design an electronic interface circuit to be integrated on the same chip as the sensors. A behavioral model of one of these sensors is set out in this paper. It is designed to be included in the model of the microsystem-to-be. It is based on experimental results on the static and dynamic responses of the sensor to humidity and temperature changes. Simulation results fit experimental data with an error inferior to 1%. The model is an illustration of VHDL-AMS capabilities as a modeling language to describe physical phenomena. The method of modeling can be extended to other kinds of sensors. Including the model in a simple microsystem model provides encouraging results.

***Keywords***: Humidity Sensor, Capacitive Sensor, VHDL-AMS Modeling, Analog Behavioral Models.

## 1 INTRODUCTION

The capacitive sensor was designed in compatible CMOS technology [1,2]. It is shown in figures 1 and 2. The sensitive layer is 1.6 µm thin. Its surface area is 9 $mm^2$. It is composed of BenzoCycloButene (BCB 4024-40 from Dow Chemical Company). Its permittivity is equal to 2.65 when it is dry. Electrodes are made of Titane-Gold, which does not oxidize in contact with humid environments. They are 1.4 µm thin. The lower electrode is a plate. The upper electrode is a grid that was deposited on the sensitive layer. Each bar of the grid is 20 µm wide and 3 mm long. The sensitive layer was plasma etched to facilitate adhesion of metal. In addition, etching created more sites for water molecules to be adsorbed on the surface of the sensitive layer. The latter is thus more sensitive to humidity, and adsorption is more significant than absorption.

When a patient blows on the sensor, humidity penetrates the sensitive layer through the upper openwork electrode (Fig. 1). The permittivity of BCB is related to the amount of water adsorbed or desorbed in it. A measure of relative humidity in breath is provided by the resulting change in capacitance. The device is heated by a resistor so that its temperature remains constant and close to breath temperature during measurements (Fig. 2). It avoids condensation and makes calibration easier. Desorption of water is accelerated if temperature rises at the end of measurements.

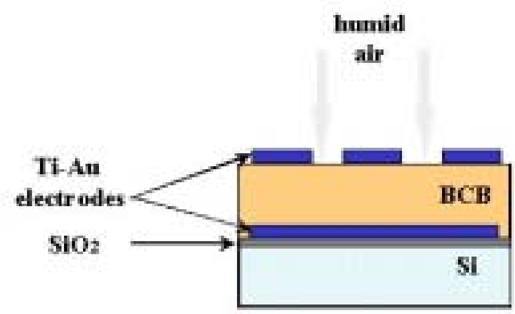



Figure 1: Cross-sectional view of the capacitive humidity sensor.

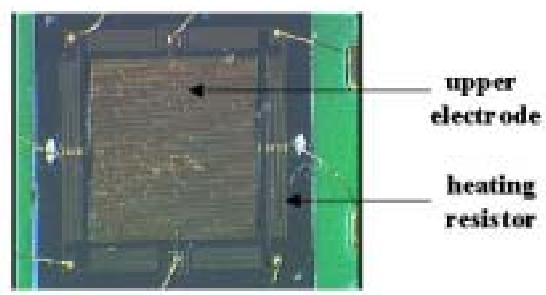



Figure 2: Top view of the capacitive humidity sensor.

The microsystem-to-be will include a measurement circuit (readout circuit), which provides a voltage proportional to the capacitance of the sensor (Fig. 3). It will also include a heating control circuit (i) to regulate temperature during measurements, and (ii) to increase the temperature when it determines that measurements are finished.

The microsystem model hence includes electrical and non-electrical subsystems linked by signals of different natures (Fig. 3). These signals are humidity, temperature, capacitance, voltage, and electric power. Separate simulation of the electrical and the physical parts is not relevant since (i) they have the same importance for the functioning of the microsystem, and (ii) temperature has an influence on each subsystem. Simulation of the whole microsystem is needed (i) to design the readout circuit and the heating control circuit, (ii) to test general sensitivity to temperature, and (iii) to design auto-calibration. A Top-Down design methodology was chosen. The models were constructed thanks to VHDL-AMS (Analog Mixed Signal) for the following reasons [3,4]. First, its syntax is fitted to describe non-electrical signals like electrical signals. Second, the system can be simulated mixing different levels of complexity. VHDL-AMS carries out transistor-level simulation as well as behavioral, and system-level simulations. To make the simulation effective, the models should be no more detailed or accurate than the level of design abstraction being used at this point in the design flow. Lastly, this language can simulate loops quite easily. VHDL-AMS has already displayed good results at microsystem simulating [5]. In this work, all the subsystems were modeled at the behavioral level. Simulations were carried out by ADVance MS simulator (v1.3_1.1, Mentor Graphics).

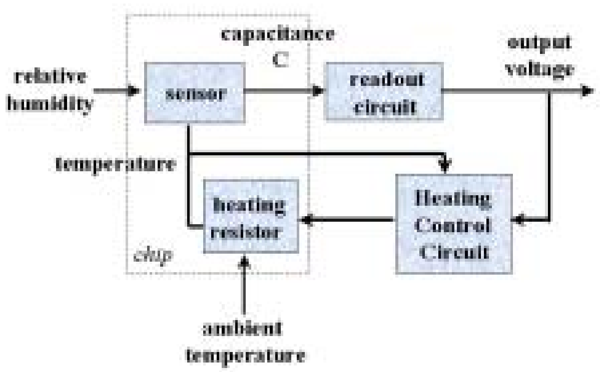



Figure 3: Block diagram of the microsystem model.

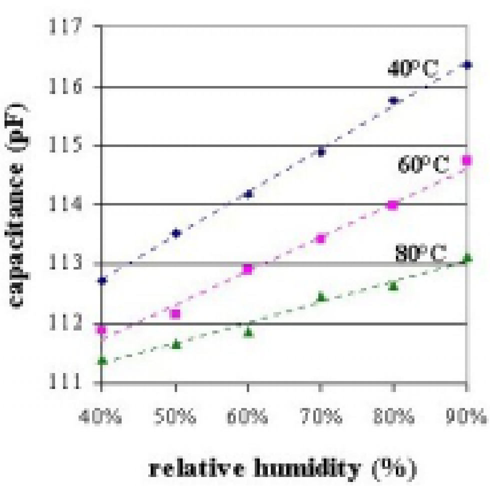



Figure 4: Linearization of experimental results.

## 2 SENSOR MODELING

### 2.1 Static Modeling

The static response is expressed as follows:

$$C = (\alpha \times \theta + \beta) \times RH + \delta \quad (1)$$

where $\theta$ represents the temperature resulting from ambient and heating conditions, and $RH$ the relative humidity surrounding the sensor. Linearization of experimental curves provided parameters $\alpha$, $\beta$ and $\delta$ (Fig. 4).

### 2.2 Dynamic Modeling

The dynamic behavior is modeled by a first-order system. Time constants for adsorption and desorption are different. The model is therefore based on two first-order circuits (Fig. 5). The upper switch is closed when humidity is adsorbed, the lower switch when humidity is desorbed.

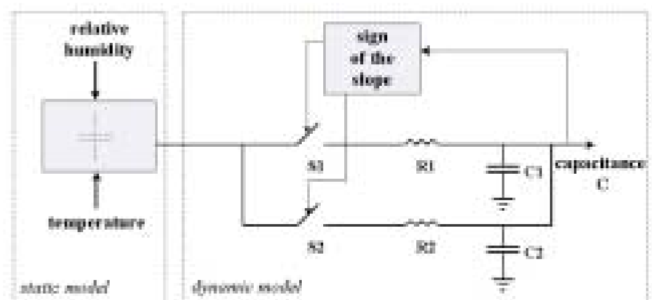



Figure 5: Schematic representation of the sensor model.

The temperature-dependence of the response time and of the desorption time is expressed by temperature-dependent resistors R1 and R2 (Fig. 5):

$$R_i = R_{0i} - \gamma_i \times \theta \quad (2)$$

Parameters $R_{0i}$ and $\gamma_i$ were set in keeping with experimental data. The adsorption time is about 770 ms at 40 degrees centigrade and about 715 ms at 60 degrees centigrade. The desorption time is about 2.2 s at 40 degrees centigrade and about 1.275 s at 60 degrees centigrade.

### 2.3 VHDL-AMS Coding

The elements of the model shown in figure 5 were described at the behavioral level. Relative humidity, temperature and capacitance were declared with the keyword "quantity" so that their differential and algebraic equations would be solved by the analog solver. Physical quantities can be either "across" quantities or "through" quantities. "Across" quantities represent effort while "through" quantities represent flow. We accordingly declared humidity, temperature and capacitance as “across” quantities and coded them as if they were voltages.

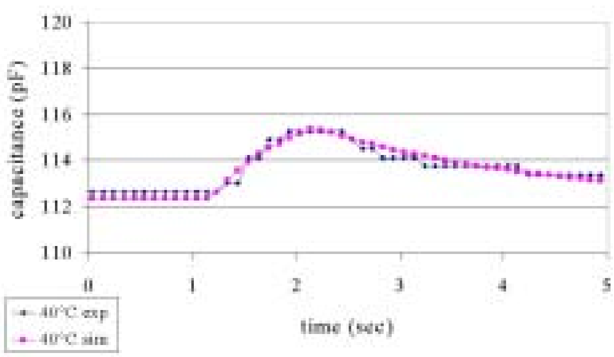
The static model is expressed by equation (1).

Capacitances were given constant values. Resistor values were calculated by equation (2). Two architectures were implemented for resistors, one for adsorption and another for desorption.

The “sign of the slope” block includes three concurrent processes. The input and the output of this block are “quantities” in order to perform the interface with the other blocks. Internal signals were declared as “signals” because this type is the basic support for event-driven modeling. The first process describes a clock signal whose period was 200 µs. The second one (i) samples the input of the block $V_{in}(t)$ at each clock rising edge to generate signal $V_{in}(n)$, (ii) calculates $V_{in}(n)-V_{in}(n+1)$, and (iii) compares it to a level to determine the output. The third one samples $V_{in}(n+1)$, at each clock falling edge. The level of comparison corresponds to the value of $V_{in}(n)-V_{in}(n+1)$ for which changes in humidity are sufficiently large to consider that adsorption occurs.

# 3 RESULTS

(a)




(b)

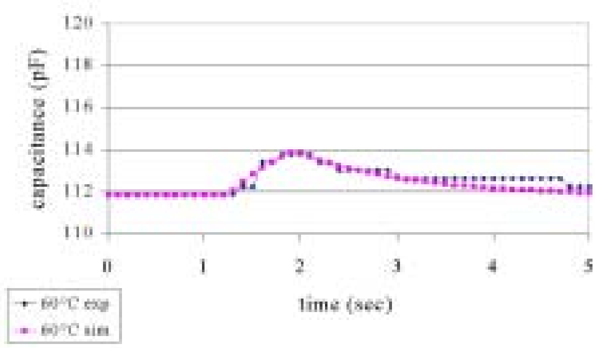



Figure 6: Comparison between experimental and simulated response of the sensor to a humidity step from 35% to 90% (a) at 40°C, (b) at 60°C

## 3.1 Sensor Simulation

Responses to humidity steps were compared to experimental data obtained in real breathing conditions (Fig. 6 a and b). The steps varied between 35% and 90% relative humidity. Comparison was made for heating temperatures of 40 degrees centigrade and of 60 degrees centigrade. The rising time and the falling time of the steps were 0.1 s. The step duration was 1 s. Thirty-five per cent relative humidity corresponds to the ambient humidity when the experiments were carried out. Ninety per cent relative humidity corresponds to humidity in a healthy breath. The maximum difference between experimental and simulated data was 0.6%, the average difference was 0.2%. Cpu time was about 5 s to perform a simulation of 30 s.

## 3.2 System-level Simulation

The static behavior of the heating resistor was modeled thanks to experimental data. The dynamic behavior was expressed by a first-order system (Fig. 7). A delay stands for thermal inertia.

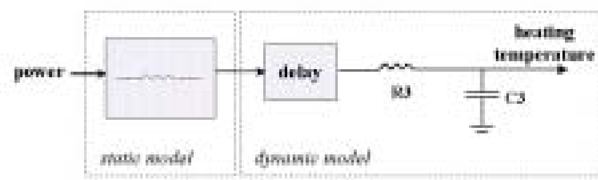



Figure 7: Schematic representation of the heating resistor model

The readout circuit was modeled by the typical equation of switched-capacitor amplifiers:

$$V_{out} = \frac{C}{C_{reference}} \times V_{reference} \quad (3)$$

The model of the heating control circuit includes a “sign of the slope” block similar to the one used to model the sensor (Fig. 8). If the slope is equal to or greater than zero, the power applied to the heating resistor is set at the value needed to heat the device up to 37°C. If the slope is negative, the power applied corresponds to a temperature close to 70°C.

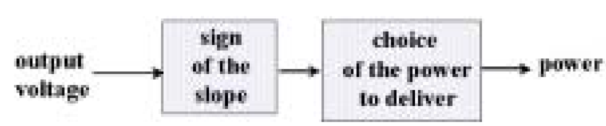



Figure 8: Schematic representation of the heating control circuit

A humidity step from 2% to 98% was applied to the input of the microsystem model. Ambient temperature was set at 20°C. Curves respectively set out the model behavior when heating was off, and when heating was on (Fig. 9 a and b). When heating was on, temperature rose at the beginning of desorption. These results pointed out the influence of the heating system on the desorption time. Cpu time was about 12 s to perform a simulation of 30 s.

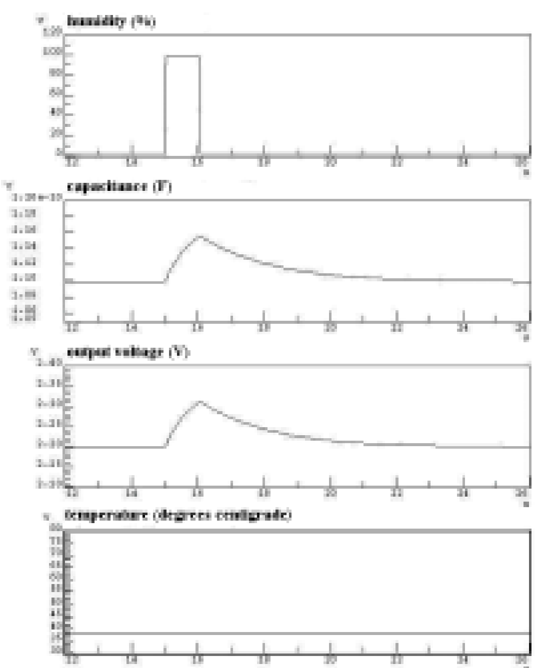
## 4 CONCLUSIONS

The sensor model has shown satisfactory results in comparison with experimental data.

The method to model dynamics lies in switching on several first-order systems whose resistor values are calculated according to physical parameters. The number of first-order circuits is equal to the number of possible physical states (for the model presented, adsorption and desorption). The parameters of modeling resistors depend on the physical quantities which have an influence on response time (temperature). This method could be extended to other kinds of sensors.

The simple model presented here is an essential step towards further improvements. The microsystem model is an easy framework to develop thanks to VHDL-AMS flexibility.

(a)




(b)

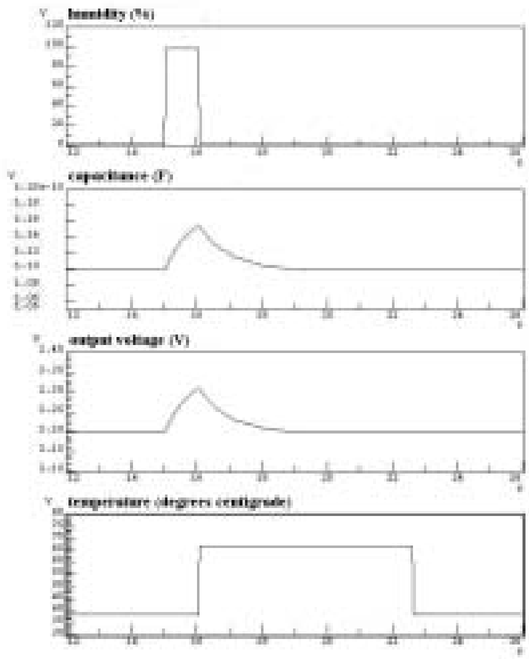



Figure 9: Simulation results of the VHDL-AMS microsystem model: (a) when heating is off, (b) when heating is on.

## REFERENCES

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