A Low-Power Robust Humidity Sensor in a Standard CMOS Process

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Abstract—This paper presents a low-cost thermal-conductivity-based humidity sensor implemented using a 0.6-μm CMOS process, where suspended p-n junction diodes are used as the humidity-sensitive elements. The measurement method uses the difference between the thermal conductivities of air and water vapor at high temperatures by comparing the output voltages of two heated and thermally isolated diodes; one of which is exposed to the environment and has a humidity-dependent thermal conductance, while the other is sealed and has a fixed thermal conductance. Thermal isolation is obtained by a simple front-end bulk silicon etching process in a TMAH solution, while the diodes are protected by the electrochemical etch-stop technique. The suspended diodes are connected to an on-chip circuit using polysilicon interconnect layers in order to increase their thermal resistance to be able to heat them with less power. Due to the high electrical resistance and positive temperature coefficient of resistance of the polysilicon, temperature sensitivities of the diodes are reduced to -1.3 mV/K at a 100-μA bias level. The diodes and the readout circuit are monolithically integrated using a standard 0.6-μm CMOS process. Characterization results show that humidity sensitivity of the sensor is 14.3, 26, and 46.9 mV/%RH for 20 °C, 30 °C, and 40 °C, respectively, with a nonlinearity less than 0.3%. Hysteresis of the sensor is less than 1%. The chip measures 1.65 mm × 1.90 mm, operates from a 5-V supply, and dissipates only 1.38-mW power.

Index Terms—CMOS humidity sensor, humidity sensor, microelectromechanical system (MEMS) humidity sensor.

I. INTRODUCTION

HUMIDITY sensors have a wide range of application areas, including agriculture, climate control, food storage, and domestic appliances. In order to satisfy the requirements of these applications, humidity sensors should provide high sensitivity over a wide range of humidity and temperature, low hysteresis, and linear response. Other important parameters of the humidity sensors can be listed as long-term stability, response time, and power consumption. A desirable feature of the humidity sensors is their compatibility with standard IC fabrication technologies. There are various types of humidity sensors based on the sensing principle they use, such as resistive, mechanical, gravimetric, capacitive, and thermal humidity sensors.

Resistive-based humidity sensors mainly use ceramics and polymers as humidity-sensitive materials, including TiO_2, $LiZnVO_4$, $MnWO_4$, C_2O, and Al_2O_3 [1]–[3]. In general, ceramics have good chemical stability, high mechanical strength, and resistance to high temperature. However, they have nonlinear humidity-resistance characteristics and are not compatible with standard IC fabrication technologies. Polymer-based resistive humidity sensors are another type of resistive humidity sensors that are present in the literature. Impedance changes of polyvinyl alcohol, phthalocyaninosilicon, and nafion with relative humidity (RH) have been examined and reported [4]. Polymers also have nonlinear humidity-resistance characteristics.

Mechanical humidity sensors use humidity-dependent mechanical stress of polyimide films [5], [6]. It has been reported that humidity-induced extension of polyimide films is quite linear in a wide range of humidity. Using the humidity-induced swelling property of polyimide thin films, piezoresistive humidity sensors have been developed [6]. Main disadvantages of these sensors are their sensitivity to ambient temperature and pressure variations.

Gravimetric humidity sensors uses the fact that the change of mass due to the humidity absorption changes the resonance frequency of the quartz resonators such as quartz crystal microbalance [7]. Humidity-absorptive properties of fullerene films have been investigated by means of their effect on the resonance frequency of quartz resonators [8]. Test results have shown that the resonators provide very high sensitivity and low response time, but the frequency change with respect to the RH demonstrates exponential characteristics.

Capacitive technique is the most widely used technique for humidity sensors, where the RH change is detected by the humidity-induced dielectric constant change of thin films. The most widely used materials as humidity-sensitive dielectrics are polyimide films, as they provide high sensitivity, linear response, low response time, and low power consumption [9]–[13]. The use of polyimide films allows the implementation of the humidity sensors together with integrated circuits. However, polyimide films suffer from long-term reliability and chemical durability problems, especially in harsh environments [14]. Furthermore, polyimide-based humidity sensors fail to operate properly when water condensation occurs on the sensor surface at high RH levels, which can be eliminated using additional elements such as on-chip or off-chip heaters, increasing the cost of the device [10]. This problem is inherently eliminated with the thermal-conductivity-based humidity-sensing approach.

Thermal-based humidity sensors use the difference between the thermal conductivity of air and that of water vapor at elevated temperatures. There are already two approaches that are used to implement humidity sensors using the thermal conductivity principle [15], [16]. These sensors use heated metal resistors on two different diaphragms as sensing elements; one
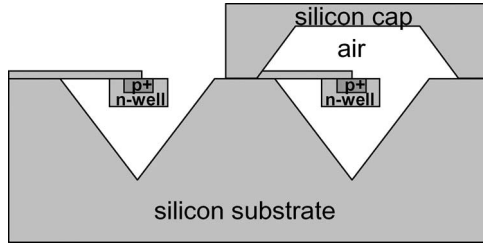
Fig. 1.   Cross-sectional view of the thermal-conductivity-based humidity sensor structure.

of which is exposed to the humid environment that causes the resistor to cool down with increased humidity, while the other one is sealed from the environment [15], [16]. This method not only prevents condensation of water on the sensing elements but also provides a linear response, low hysteresis, and long-term stability. However, the use of metal resistors as heating and sensing elements has various drawbacks, as metal resistors require high power dissipation to reach the desired temperature levels for thermal-conductivity-based humidity measurement. Furthermore, the implementation methods of the sensors in literature are not CMOS compatible; therefore, the sensor and the readout circuit need to be hybrid-connected for further signal processing of the sensor output, increasing the cost and decreasing the reliability of the sensor. To eliminate the drawbacks of previous humidity sensor approaches, there is a need for a new approach to implement low-cost, low-power, and high-performance humidity sensors. This paper presents the development of such a humidity sensor.

The proposed humidity sensor is based on thermal conductivity, but sensor elements are achieved using suspended diodes that require less power for heating while providing the required sensitivity [17]. The humidity sensor is implemented by post-CMOS processing of CMOS fabricated chips to obtain suspended and thermally isolated diodes. This approach allows the monolithic integration of the sensor and its readout circuit on the same substrate. The humidity sensor implemented with this approach also provides a linear response and low hysteresis.

II. SENSOR STRUCTURE

Fig. 1 shows a cross-sectional view of the proposed thermal-conductivity-based humidity sensor structure. There are two diodes: One of them acts as the sensor diode, while the other acts the reference diode. The reference diode is sealed from the environment by attaching a silicon cap, and the sensor diode is exposed to the environment. Both of the diodes are suspended to achieve thermal isolation from the substrate; therefore, each one is easily heated to temperatures in the range of about 250 °C with a power of 0.1 mW, i.e., the power for heating the diodes is only a small portion of the total power consumption of the sensor chip, which is 1.38 mW. The exposed diode will have humidity-dependent thermal conductance, while the sealed one will have a fixed thermal conductance. Therefore, the diodes will heat up to different temperature levels, providing different diode turn-on voltages. By comparing the diode voltages of the reference and the sensor diodes, it is possible to determine the humidity level.
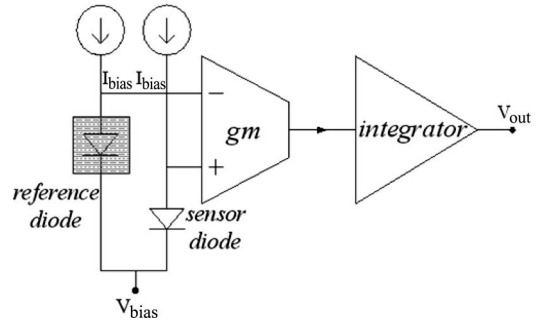

Fig. 2.   Block diagram of the humidity sensor together with its readout electronics.

This approach provides a number of advantages. The diodes can be heated up with a low power, and they provide high sensitivity. As the diodes are heated up, no water condensation can occur on the sensing elements. The fabrication process is CMOS compatible and requires only a simple etching step after CMOS process, i.e., the sensor can be fabricated at low cost. Also, the readout circuit can be integrated with the sensor, which is important to obtain higher sensitivity, better noise performance, and smaller sensor.

III. SENSOR SYSTEM DESIGN

Fig. 2 shows the block diagram of the humidity sensor together with its readout electronics. The sensor is composed of a reference, a sensor diode, and on-chip readout circuitry. Both of the diodes are heated by applying constant currents up to a temperature of approximately 250 °C, at which the thermal conductivity of water vapor is higher than the thermal conductivity of air [16]. The sensor diode is exposed to the environment, while the reference diode is sealed and isolated from the environment. The thermal conductance of the sensor diode increases with the increasing amount of water vapor, which results in a decrease of the temperature of the diode. Due to the negative temperature sensitivity of the diode, the output voltage of the sensor diode increases, while the output voltage of the reference diode remains constant. The difference between the diode voltages is converted into a current by a differential transconductance amplifier, and this current is integrated through a switched capacitor integrator in order to obtain an amplified output signal with a gain of 60 dB. Fig. 3 shows the detailed circuit diagram of the integrated humidity sensor.

There are a number of parameters that need to be considered in the design of the thermal-based humidity sensors to achieve high performance and sensitivity. One of the most important parameters that affect the sensitivity is the temperature sensitivity of the sensor element, which is selected as a p-n junction diode, as they provide higher sensitivity compared to resistors. Temperature sensitivity of a p-n junction diode is given by [18]

$$\left.\frac{dV}{dT}\right|_{dI=0} = \frac{V}{T} - V_T\left(\frac{1}{I_s}\frac{dI_s}{dT}\right) \tag{1}$$

where V is the diode voltage, T is the temperature, V_T is the thermal voltage, and I_s is the saturation current of the diode.
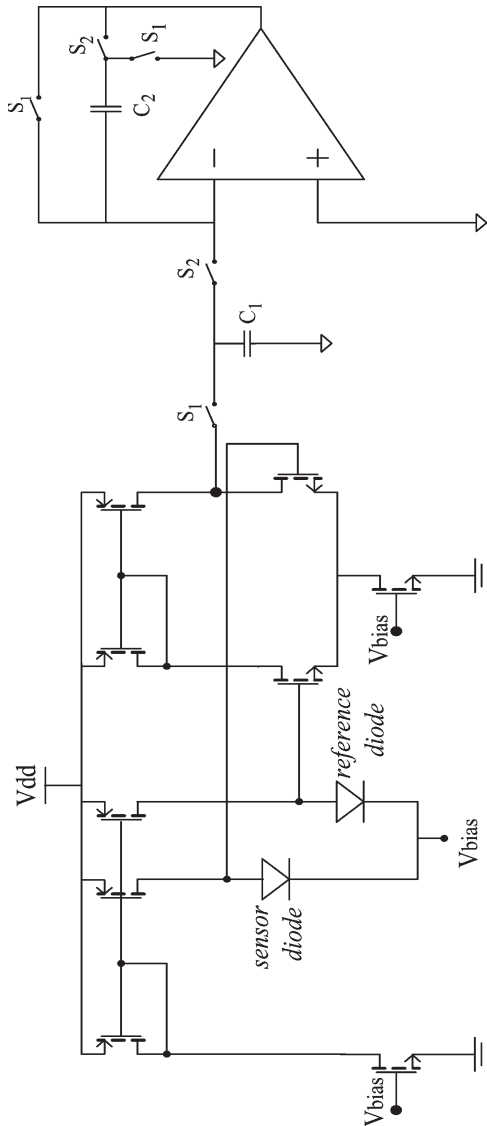
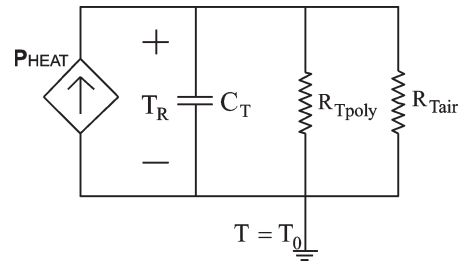Fig. 3. Detailed circuit diagram of the integrated humidity sensor.

Fig. 4. Lumped element thermal circuit representing the self-heating of a diode biased with a constant current.

the thermal capacitance. According to the humidity-sensing principle, the temperature of the diode should change when exposed to humidity. This change comes from the change in the thermal conductivity of the air surrounding the diode due to the presence of water vapor. Consequently, it can be stated that, to be able to sense the humidity, the thermal conductance of air should be larger than the thermal conductance of the interconnections of the diode. In other words, the thermal conductance of the interconnection should be as small as possible in order to increase humidity sensitivity. Low thermal conductance of the interconnect layer also helps in heating up the diodes to the high temperatures required for humidity measurements with less power.

Electrical connections from the diodes to the circuit are obtained using polysilicon interconnect layers. Polysilicon is used instead of a metal layer due to its low thermal conductivity. However, using the polysilicon as the interconnect layer reduces the overall temperature sensitivity of the structure due to its high electrical resistivity and positive temperature coefficient of resistance (TCR) property. This phenomenon can be explained mathematically as follows. The total voltage of the diode and the interconnections is expressed as

$$V = V_d + iR \tag{2}$$

where V_d is the diode voltage and i and R are the bias current and the interconnect resistance, respectively. If the derivatives with respect to the temperature are taken in both sides

$$\frac{\partial V}{\partial T} = \frac{\partial V_d}{\partial T} + i\alpha R \tag{3}$$

where α is the TCR of the interconnections. Since temperature sensitivity of the diode is negative and the TCR of the polysilicon is positive, the overall temperature sensitivity of the structure is reduced due to the high electrical resistance of the polysilicon interconnect layer. Although the use of polysilicon interconnect negatively affects the sensitivity of diodes, it is still preferred as the overall sensitivity of the structure is more dependent on thermal isolation.

Another important parameter in (3) is the bias current. As the bias current increases, the overall temperature sensitivity of the structure also decreases. However, the bias current cannot be lower than a certain value to guarantee self-heating of the diodes. Self-heating is dependent on the thermal conductance, which is affected by the geometrical parameters of the diode structure. Moreover, the geometry of the diodes affects the postprocessing conditions and results, which is another

The most important advantage of p-n junction diodes is that they have high and almost constant temperature sensitivity in a wide range of temperature. At a constant forward current, the temperature sensitivity of a silicon p-n junction diode is approximately -2 mV/$^\circ$C. In addition, they can be implemented in any standard CMOS process, i.e., it is very easy to achieve the monolithic integration of the sensing element with the readout circuit.

Another very important parameter that affects the sensitivity of thermal-based humidity sensors is the thermal isolation of the sensor elements from the bulk silicon. The thermal conductance of the diode structures depends on two main parameters: One of them is the thermal conductance of the interconnections of the diode to the readout circuit, and the other one is the thermal conductance of the air between the diode and the substrate [19]. Fig. 4 shows the lumped element thermal circuit representing the self-heating of a diode biased with constant current. In Fig. 4, R_{Tpoly} and R_{Tair} represent the thermal resistances of the polysilicon interconnections and air between the diode and the substrate, respectively, while C_T represents

Fig. 5. Temperature sensitivity and the operating temperature versus the bias current curves.

Fig. 6. Layout of the thermal-conductivity-based humidity sensor designed in a 0.6-μm CMOS process.

critical task in the implementation of the sensor. Therefore, the optimization of the diode parameters is a complex task, in which all the electrical and physical effects should be taken into account. In the design phase, the physical dimensions of the diode structures are first determined, considering the minimum opening sizes that would guarantee the successful etching of the bulk silicon under the diode in TMAH for obtaining suspended diodes. Other parameters are then determined, considering the operating temperature and sensitivity. For the selected diode dimensions, the thermal conductance of air and the interconnections are 3.64×10^{-7} and 1.58×10^{-8} W/K, respectively, resulting in an overall thermal conductance of 3.80×10^{-7} W/K. This overall thermal conductance allows heating of each diode to the determined operating temperature of about 250 °C with a very small heating power of 0.1 mW. It should be noted again that the operation temperature of the diodes is selected as 250 °C as the thermal conductivity of water vapor at this temperature is higher than the thermal conductivity of air [16]. In order to determine the necessary bias current that is used to heat the diodes to 250 °C and the temperature sensitivity of diodes at this temperature, a theoretical analysis is performed, considering the determined diode geometrical parameters and using thermal equations [19]. Fig. 5 shows the diode temperature and the overall temperature sensitivity versus the bias current curves. The calculated temperature sensitivity of the diodes is −1.3 mV/K at 250 °C and 100-μA bias. It should be noted here that the temperature sensitivity of the diodes is less than −2 mV/K, mainly due to the effect of polysilicon interconnect layers in the arms.

IV. FABRICATION AND TEST RESULTS

Fig. 6 shows the layout of the thermal-conductivity-based humidity sensor designed in a 0.6-μm CMOS process. The sensor and reference diodes are monolithically integrated with the readout circuit. The reference diode is placed in the middle of the chip and surrounded by a metal layer, which can be used to attach a silicon cap to isolate the reference diode from the environment. After the standard CMOS fabrication, diodes
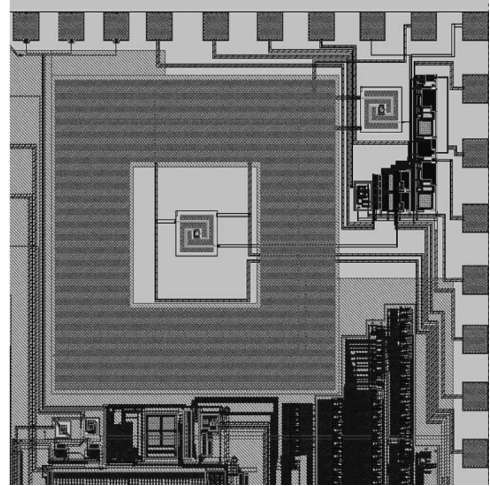
are suspended by a front-end anisotropic bulk-silicon etching process in a TMAH solution.

The most important part of the anisotropic bulk silicon etching process is the protection of the diodes against the etchant. In this process, electrochemical etch stop technique was used [20]. Electrochemical etch stop was performed using four electrode etch control configuration. In the four-electrode configuration, p- and n-type silicon are biased at the same time with respect to the etching solution. The potential of the solution is measured with a reference electrode and fed back to a potentiostat, which continuously controls the bias voltages.

Before starting the process, 16 gr/lt of silicon powder was dissolved in 5% TMAH solution to prevent the etching of aluminum. At the beginning of the etching, 0.4 gr/100 ml of ammonium peroxidisulfate $((NH_4)_2S_2O_8)$ was also added to the etching solution. This material prevents the formation of hillocks on the surface, but it slows down the etching process [21]. At the beginning of the etching process, there is no need to bias the n-well layer since the n-well is not directly exposed to the solution. Furthermore, when the passivation voltage is applied, the etch rate decreases. Therefore, in order not to decrease the etch rate at the beginning of the process, n-well was not biased. The time it takes for the solution to reach the n-well was determined experimentally, and the etch stop potential was applied accordingly. Table I gives the important parameters of the TMAH etching and electrochemical etch stop processes. Figs. 7 and 8 show the SEM pictures of the fabricated humidity sensor chip and one of the suspended diodes, respectively. It should be mentioned that there is a small warping on the arms of the suspended diodes due the stress of the films; however, this warping is not expected to affect the sensor operation as the warping is small, and it similarly occurs in both diodes.

In order to test the sensor, the reference diode should be isolated from the humid environment. During the initial tests of the prototypes, isolation is achieved by attaching a small silicon cap on top of the reference diode using epoxy. This approach can be used only for relatively short-term tests. For high volume batch fabrication and long-term use, one of the wafer level

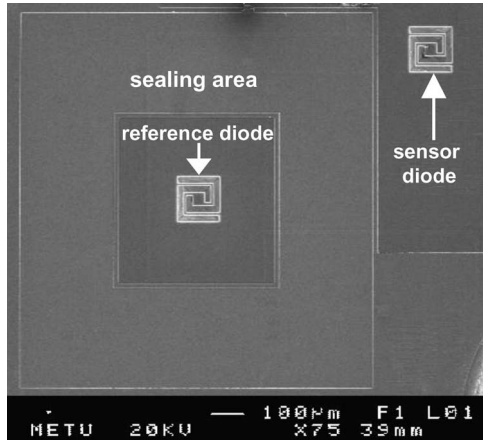| Etchant	$(NH_4)_2S_2O_8$ amount	Pre-etch duration	Substrate bias	N-well bias	Etch duration
5% Si doped TMAH	0.4gr/100ml	5 minutes	-1.45 V	0 V	3 hours

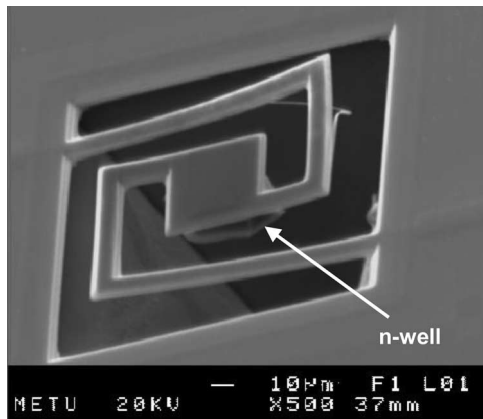Fig. 7. SEM picture of the fabricated humidity sensor chip.

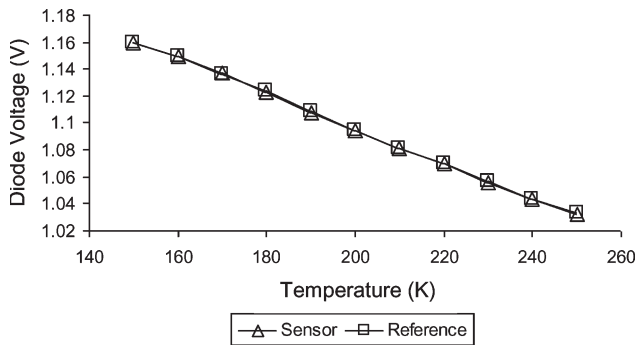Fig. 8. SEM picture of one of the suspended diodes.

Fig. 9. Diode voltages measured at a 100-μA bias level with respect to the ambient temperature.
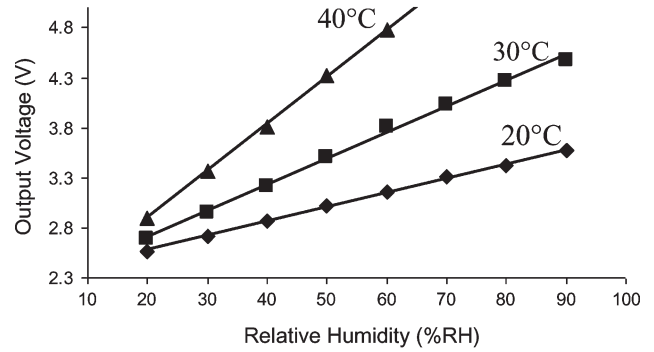

Fig. 10. Measurement results of the humidity sensor. It provides sensitivities of 14.3, 26, and 46.9 mV/%RH for 20 °C, 30 °C, and 40 °C, respectively, with a nonlinearity less than 0.3%.

(a)

(b)
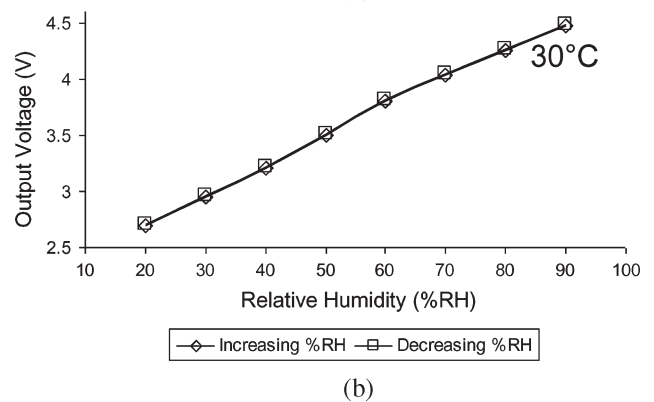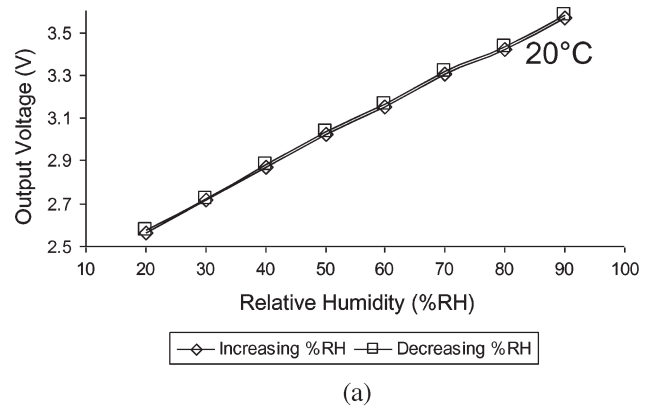
Fig. 11. Measured hysteresis characteristics of the humidity sensor at (a) 20 °C and (b) 30 °C, which are less than 1%.

packaging methods that are available in the literature can be used [22], [23].

The characterization of the sensor requires a number of steps. First of all, it is important to set the operating temperatures of the sensors to 250 °C, as explained in Section III. This is not an easy step as it is not easy to directly measure the diode temperature. One method that is used to determine the operating diode temperature is to use the diode itself as a temperature sensor. In order to do this, the diode voltage with respect to temperature should be characterized using an unsuspended diode and a temperature oven. Fig. 9 shows the diode voltages measured

TABLE II
COMPARISON OF THE PERFORMANCE PARAMETERS OF THIS SENSOR TO SOME OF THE HIGH-PERFORMANCE HUMIDITY
SENSOR DESIGNS PRESENT IN THE LITERATURE

Ref No.	Sensitivity	Power Dissipation	Hysteresis	Water condensation problem	Monolithic integration
9	0.003 μA/%RH	1 mW	<1%RH	Possible	Yes
10	30 fF/%RH	37 mW	Not indicated	Possible	No
12	25 mV/%RH	Not indicated	<1%RH	Possible	No
13	3.4 pF/%RH	Not indicated	<2%RH	Possible	No
15	0.054 mV/%RH	165 mW	<1%RH	Not possible	No
This work	46.9mV/%RH	1.38 mW	<1%RH	Not possible	Yes

at a 100-μA bias level within the temperature range from 150 °C to 250 °C. This measurement shows that the diode voltage is 1.03 V for 250 °C at a 100-μA current. When a suspended diode is biased at 100 μA, its voltage was also 1.03 V, verifying that the suspended diode temperature is also 250 °C. Fig. 9 can also be used to determine the temperature sensitivity of the diodes, which is measured as -1.3 mV/K. Based on these measurements, it can be concluded that the theoretical model used in the production of the curves in Fig. 5 is accurate for this design. It should be noted that the mismatch between the sensor and reference diode voltages is also measured, and it is determined to be less than 1 mV, which is very small due to their implementation on the same CMOS chip.

Fig. 10 shows the characterization results of the sensor within the 20%–90% RH range for 20 °C, 30 °C, and 40 °C ambient temperature levels. Sensitivity of the chip is measured as 14.3, 26, and 46.9 mV/%RH for 20 °C, 30 °C, and 40 °C, respectively, with a nonlinearity less than 0.3%. The total power dissipation of the system is measured as 1.38 mW. At 40 °C, the output voltage saturates to the positive supply voltage after 60% RH due to the high gain of the circuit. Noise measurements show that the resolution of the sensor is less than 1%RH. This value is well below the resolution requirement of the common humidity-sensing applications, which is around 2–3%RH.

The RH response of the chip is highly temperature dependent, which is an expected result, since the sensor output depends on the thermal conductance of the surrounding air, which is related with the absolute amount of moisture in air. Consecutively, the sensitivity of the sensor increases with the increasing ambient temperature due to the fact that the amount of moisture is higher at a higher temperature for the same RH level. This is a general fact for humidity sensors, and a temperature sensor should be used with humidity sensors. One of the advantages of the sensor approach in this paper is that it allows easy and monolithic integration of a temperature sensor to the CMOS chip [24], [25].

Hysteresis of the sensor is also measured inside the environmental chamber by increasing the RH from 20% to 90% and then decreasing back to 20%. Measurements were performed after waiting 30 min at every measurement point to allow the settling of the humidity level and temperature in the chamber. During the decrease of the humidity level, the moisture content of the sensor cavity does not reduce with the same amount as the environment. This is due to the fact that a small amount of moisture is absorbed by the surface of the layers that create

the sensor and affects the overall thermal conductivity of the air inside the cavity. This effect might result in a very small hysteresis. Fig. 11 shows the measured hysteresis of the sensor, which is less than 1% at 20 °C and 30 °C ambient temperature conditions.

Any drift in the sensor response is not expected due to electrical parameters as the sensor elements are standard CMOS materials, and their electrical parameters do not drift due to the moisture or temperature around 250 °C. However, as a general problem in any post-CMOS front-etched sensor, the sensor cavity can be filled up by dust or a similar material in a real operational environment, causing drift in the sensor output. This problem can be reduced or prevented with proper selection of the sensor location, orientation, and package.

These measured results verify that the thermal-conductivity-based CMOS humidity sensor operates as designed, providing a high sensitivity and low hysteresis while operating at a low power. Table II demonstrates a comparison of the performance parameters of this sensor to some of the high-performance humidity sensor designs present in the literature. It can be concluded that the presented sensor shows better overall performance in terms of sensitivity, power dissipation, and hysteresis. In addition, there is no risk of water condensation on the surface of the sensor since the sensor operates at a temperature of 250 °C. Furthermore, it has the advantage of monolithic integration, which greatly reduces the production cost in case of a batch fabrication.

V. SUMMARY AND CONCLUSION

This paper presents a thermal-conductivity-based humidity sensor implemented using thermally isolated p-n junction diodes obtained by standard CMOS and post-CMOS bulk silicon micromachining processes. Thermal isolation is achieved by anisotropic bulk silicon etching using electrochemical etch-stop technique in a TMAH solution. One of the suspended diodes is sealed and has a fixed thermal conductance, while the other one is exposed to ambient and has a humidity-dependent thermal conductance; therefore, they provide different diode voltages when they are heated with same biasing currents. The difference in the diode voltages is amplified using a CMOS readout circuit, which is implemented monolithically with the diodes during the CMOS fabrication.

A prototype of the sensor has been fabricated and characterized. Table III summarizes the characterization results

TABLE III
SUMMARY OF THE THERMAL-CONDUCTIVITY-BASED HUMIDITY SENSOR PARAMETERS

Parameter		Value
Process		0.6μm CMOS
Power Supply		5V
Power Dissipation		1.38mW
Chip Size		1.65mm x 1.9mm
Humidity Sensitivity	20ºC	14.3 mV/%RH
	30ºC	26 mV/%RH
	40ºC	46.9 mV/%RH
Hysteresis	20ºC	< 1%RH
	30ºC	< 1%RH

and important parameters of the thermal-conductivity-based humidity sensor. The measured temperature sensitivity of the diodes is -1.3 mV/K within 150 °C–250 °C range at a 100-μA bias level. RH sensitivity of the sensor is 14.3, 26, and 46.9 mV/%RH for 20 °C, 30 °C, and 40 °C ambient temperatures, respectively, with a nonlinearity less than 0.3%. The measured hysteresis of the sensor is less than 1% at 20 °C and 30 °C ambient temperature conditions. Total power dissipation of the chip is only 1.38 mW. As a conclusion, this approach seems attractive for implementation of low-cost, low-power, and high-performance humidity sensors.

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