CMUT Chip with Integrated Temperature and Pressure Sensors

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Abstract—**Capacitive micromachined ultrasonic transducers (CMUTs) make extremely sensitive chemical sensors in air. In this work, we demonstrate a CMUT chemical sensor chip with integrated temperature and pressure sensors. These sensors allow the measurement of multiple environmental parameters using a single chip and allow the influence of temperature and pressure on the chemical sensors to be corrected for. Additionally, the CMUTs are designed to have low charging. We demonstrate the use the temperature sensor to correct for resonance frequency variations due to temperature. With temperature correction, we measure the drift of two chemical sensors to be 19 parts per million and 59 parts per million over 12 hours. This is progress towards being able to make continuous measurements with the chemical sensor without comparing to a reference gas.**

Keywords—CMUT, Chemical Sensor, Pressure Sensor, Temperature, Stability

I. INTRODUCTION

Capacitive micromachined ultrasonic transducers (CMUTs) make extremely sensitive gravimetric chemical sensors in air. A limit of detection of 50.5 parts per trillion (3σ) has demonstrated for dimethyl methylphosphonate, a simulant for sarin gas [1]. In addition to their excellent sensitivity, CMUT chemical sensors have advantages such as small size and low cost.

A CMUT chemical sensor consists of a group of CMUT cells with the top plate covered with a chemical-sensitive functionalization layer, which absorbs chemicals from the air. The absorbed chemicals increase the mass of the plate, which decreases the resonance frequency. The concentration of the chemical can be determined from the magnitude of the frequency shift. Like many chemical sensors, CMUTs do not have perfect selectivity, but can made selective by using arrays of sensors with different coatings and using pattern recognition techniques to identify the chemical that is present [2].

One challenge for CMUT chemical sensors is stability over long time periods. The resonance frequency of the sensor can change over time due to temperature, ambient pressure, and charging of the insulator layer. This changing baseline means that only differential measurements are possible, where the sensor response to the chemical is compared to the response to a reference gas such as nitrogen or dry air. It would be beneficial to be able to perform continuous measurements of chemical concentration.
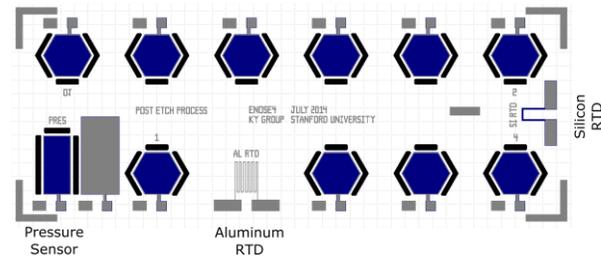

Fig. 1: Layout of the sensor chip. The pressure sensor, aluminum RTD and silicon RTD are labeled. The hexagons are the chemical sensor devices. The chip is 3.4 x 8.3 mm. The black areas around the chemical and pressure sensors are acoustic isolation trenches etched all the way through the chip.

TABLE I.   CHEMICAL AND PRESSURE SENSOR CHARACTERISITICS

	Chemical Sensors	Pressure Sensors
Number of Cells	721	216
Cell Radius (µm)	9	18
Plate Thickness (nm)	900	
Gap Height (nm)	60	
Resonance Frequency (MHz)	31	50
Collapse Voltage (V)	65	16

To address this problem, we fabricated CMUTs with integrated temperature and pressure sensors so that these parameters can be accurately measured and corrected for. In addition to helping improve the stability of the chemical sensor, the temperature and pressure sensors allow a single sensor chip to measure multiple environmental variables at once.

To further improve sensor stability, we used a modified fabrication process designed to minimize charging of the insulator layer. Charging of the insulator layer is an effect seen in CMUTs and other electrostatic devices where build-up of electrostatic charge in the insulator layer changes the effective bias voltage of the CMUT. This causes spurious changes in frequency.

II. METHODS

A. Device Design

The layout of the chip is shown in Fig. 1. Each chip has 10 chemical sensors, a silicon resistance temperature detector
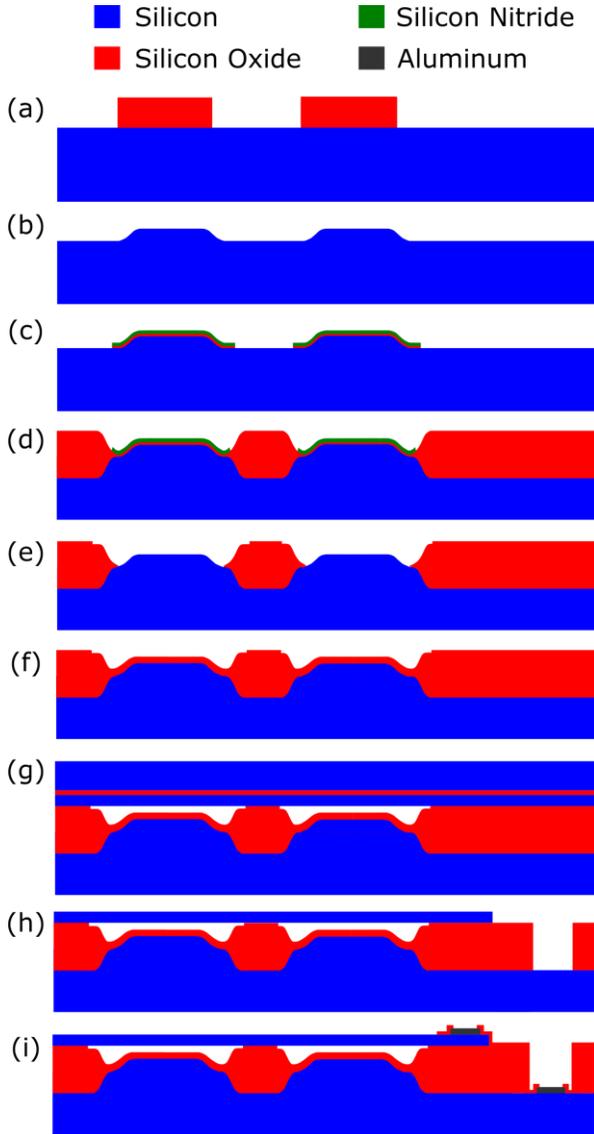
Fig. 2: Sensor fabrication process.

Fig. 3: Pressure sensor circuit schematic. The circuit is an RC relaxation oscillator with an oscillation frequency determined by the sensor capacitance.

no nitride in the insulator layer. After the local oxidation step, we etched the oxide and nitride in the cavity [Fig. 2(e)]. We then grew a new oxide insulator layer using dry thermal oxidation [Fig. 2(f)]. The silicon on insulator (SOI) wafer which forms the top plate was fusion bonded to the substrate wafer immediately after [Fig. 2(g)]. Having no process steps between insulator layer growth and SOI bonding minimizes contamination and roughening of the insulator layer. This is beneficial since the insulator layer roughness is believed to be related to dielectric charging [5].

The post region around the cavity bulges upward during the local oxidation and insulator oxidation steps [Fig. 2(d),(f)]. The bulge can cause problems with the wafer bonding step [Fig. 2(g)]. To prevent this, we etched the post area around the edge of the cavity during the step where the nitride and oxide are etched from the cavity [Fig. 2 (e)]. So, the area where the bulge forms does not form part of the bond with the top plate. This has the additional benefit of giving a better defined cell diameter than the conventional local oxidation and wafer bonding process.

The aluminum RTD and silicon RTD were defined as serpentine traces in in the aluminum bond pad layer and silicon plate layer, respectively. We deposited an oxide passivation layer on top of the sensors using chemical vapor deposition to prevent surface conduction between the serpentine traces.

The pressure sensor cells are identical to the chemical sensor CMUT cells except for their larger radius, so they are fabricated using the same steps.

C. Interface Circuits

The interface circuits were constructed on a single printed circuit board. The sensor chip was packaged in a ceramic pin grid array which was mounted in a socket on the circuit board.

The chemical sensor frequency was measured using an oscillator circuit designed to track the parallel resonance of the sensor, as described in [6]. The frequency of the output signal was measured using a frequency counter (model SR620, Stanford Research Systems, Sunnyvale, CA).

(RTD), an aluminum RTD, and a capacitive pressure sensor. The pressure sensors are CMUT cells with a larger radius so that they are more sensitive to ambient pressure. The characteristics of the chemical sensors and pressure sensor CMUT cells are given in Table 1.

B. Fabrication

The fabrication process is shown in Fig. 2. The devices were fabricated using a local oxidation and wafer bonding process [3]. This process is well-suited to CMUT chemical sensors since it allows fine control over gap height and provides low parasitic capacitance.

The local oxidation step requires a silicon nitride layer as a mask [Fig. 2(c)]. In previous work, the nitride masking layer formed part of the insulator layer in the bottom of the vacuum gap [3]. This can be a problem since silicon nitride has been shown to be more susceptible to charging problems than silicon oxide [4]. So, we developed a new version of the process with
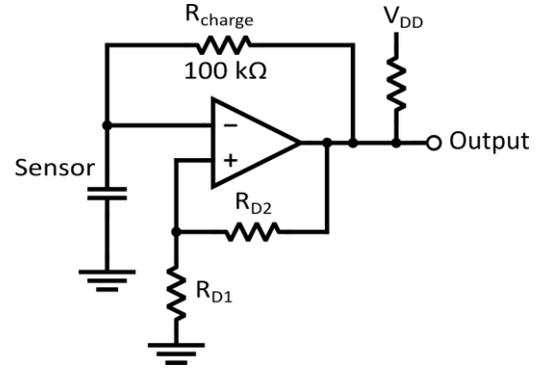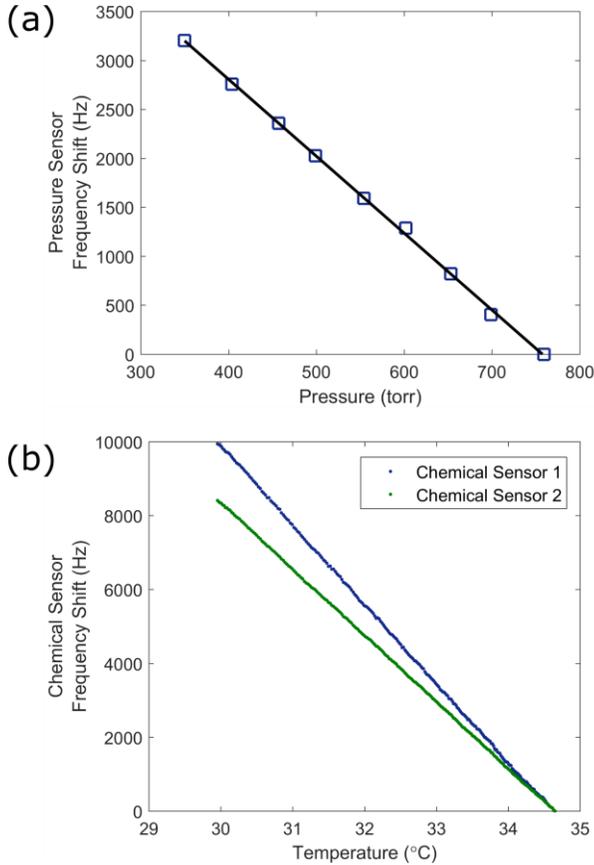
Fig. 4: (a) Pressure sensor oscillator circuit frequency vs. ambient pressure. (b) Chemical sensor frequency shift vs. temperature. The temperature is measured using the aluminum RTD on the chip.
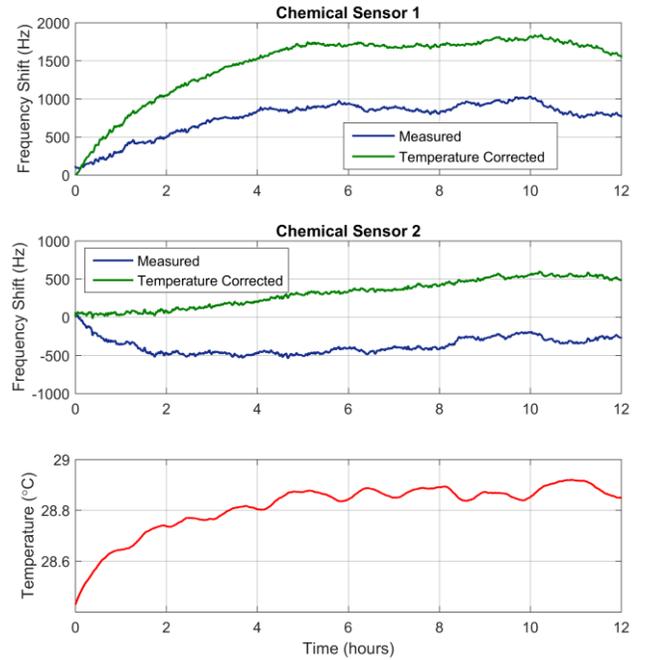
Fig. 5: (a)-(b) Chemical sensor frequency drift over 12 hours, with and without temperature correction. (c) The temperature measured by the aluminum RTD on the chip.

The bias voltage for the CMUT was provided by an LT3090 linear regulator (Linear Technology Corporation, Milpitas, CA). A stable bias voltage is essential for maintaining frequency stability, since the spring softening effect makes the CMUT resonance frequency sensitive to the bias voltage.

The pressure sensor capacitance was measured using an RC relaxation oscillator. A schematic of the circuit is shown in Fig. 3. The capacitor is charged alternately to a positive and then negative voltage set by R_{D1} and R_{D2}. This produces an oscillation with frequency proportional to $1/R_{charge}C$, where C is the sensor capacitance. The frequency of oscillation was design to be approximately 150 kHz, which is far below the resonance frequency of the pressure sensors. The frequency of the circuit output was measured using a frequency counter (model SR620, Stanford Research Systems, Sunnyvale, CA).

The resistance of the RTD was measured using a multimeter (model 34401A, Hewlett Packard, now Keysight Technologies, Santa Rosa, California).

III. RESULTS

A. Pressure Sensor

The pressure sensor was tested at a range of pressures using a low pressure chamber and found to have a response of -7.85

Hz/Torr [Fig. 4(a)]. The pressure sensor relaxation oscillator had a minimum Allan deviation of 0.20 Hz, which corresponds to a resolution of 0.026 Torr.

B. Temperature Sensor

The aluminum and silicon RTDs have resistances of about 165 Ω and 9.5 kΩ, respectively at room temperature.

The parallel resonance frequencies of two chemical sensors on the same chip were measured as a function of temperature using the aluminum RTD [Fig. 4(b)]. The printed circuit board containing the oscillator circuits and bias voltage regulator was heated along with the sensor chip itself, so the temperature dependence of the frequencies comes both from the sensor chip and from the interface circuits. The temperature coefficients of the sensors do not match because of differences in the temperature coefficients of the oscillator circuit components for each device, and because the chemical sensors were operated at slightly different bias voltages to avoid locking of the sensors.

C. Chemical Sensor Stability

To test the stability of the chemical sensors over time, we measured the frequency over a period of 12 hours. The CMUT frequency was found to be sensitive to light, so the sensor chip was covered with an opaque box. Nitrogen was flowed slowly through the box to remove the effect of humidity. In the future, the humidity level will be measured by the chemical sensors. The frequencies of two chemical sensors on the chip were recorded every 5 seconds with a gate time of 1 second. The temperature was measured using the aluminum RTD. A

moving average with a two minute window was performed on the data.

The measured temperature coefficients of the chemical sensors were used to correct for the effects of temperature. Fig. 5 shows the frequency change over time with and without temperature correction. The frequency of chemical sensor 1 varied by 59 parts per million (ppm) over the 12 hours, after temperature correction. The variation was much smaller after the first 4 hours. The frequency of chemical sensor 2 varied by 19 ppm.

Temperature correction was effective, but did not remove all the frequency drift from the sensors. The extra drift could be caused by charging of the insulator layer. Other factors such as drift in the bias voltage may also be responsible. The two sensors do not show the same pattern in frequency variation, so there must be some factor affecting the frequency which is unique to each sensor. It could be that the two sensors are charging at different rates.

IV. CONCLUSION

We fabricated CMUT chips with integrated temperature and pressure sensors. These sensors require no additional fabrication steps beyond those required for the chemical sensors. We demonstrated the functionality of the pressure sensors. We used the temperature sensor to correct the baseline sensor frequency for temperature variation. With the effect of temperature removed, the two CMUT chemical sensors experienced 19 ppm and 59 ppm over 12 hours. This shows progress towards being able to do continuous chemical sensing. In addition to keeping the baseline stable, the integrated sensors could be useful to deal with the effects of ambient pressure and sensor temperature on the functionalization layer sensitivity.

The CMUTs showed signs of charging in spite of our fabrication process, which was designed to reduce charging. More work is needed to eliminate or correct for charging. Attaining high stability will also require that the oscillator circuit and bias voltage source have their temperature dependence well-controlled. An application specific integrated circuit implementation of the circuit would help ensure that the circuit temperature is uniform and precisely known.

In the future, we will coat the chemical sensor CMUTs with functionalization layers to create a multi-channel chemical sensor on a single chip. We will test the ability of the system to perform continuous measurements of chemical concentration.

REFERENCES

[1] H. J. Lee, K. K. Park, M. Kupnik, Ö. Oralkan, and B. T. Khuri-Yakub "Chemical vapor detection using a capacitive micromachined ultrasonic transducer," *Anal. Chem.*, vol. 83, no. 24, pp. 9314-9320, November 2011.

[2] Q. Stedman, K. K. Park, and B. T. Khuri-Yakub, "Distinguishing chemicals using CMUT chemical sensor array and artificial neural networks," in *Proc. Of IEEE Int. Ultrasonics Symp.*, Chicago, Illinois, 2014, pp. 162-165.

[3] K. K. Park, H. J. Lee, M. Kupnik, and B. T. Khuri-Yakub, "Fabrication of capcitive micromachined ultrasonic transducers via local oxidation and direct wafer bonding," *J. Microelectromech Syst.*, vol. 20, no. 1, February 2011.

[4] S. Machida et al., "Analysis of the charging problem in capacitive micro-machined ultrasonic transducers," in *Proc. Of IEEE Int. Ultrasonics Symp.*, Beijing, China, 2008, pp. 383-385.

[5] P. Zhang, G. Fitzpatrick, T. Harrison, W. Moussa, and R. J. Zemp, "Double-SOI wafer-bonded CMUTs with improved electrical safety and minimal roughness of dielectric and electrode surfaces," *J. Microelectromech. Syst.*, vol. 21, no. 3, pp. 668-680, April 2012..

[6] K. K. Park et al., "Capacitive micromachined ultrasonic transducers for chemical detection in nitrogen," *Appl. Phys. Lett.*, vol. 91, pp. 094102, 2007.