A Capacitive Micromachined Ultrasonic Transducer (CMUT) Array as a Low-Power Multi-Channel Volatile Organic Compound (VOC) Sensor

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***Abstract*— In this study we extend our work on low-power CMUT chemical sensors from a single element to an array as a way to improve selectivity to volatile organic compound (VOC) analytes. A single channel of our sensor array comprises of a polymer-functionalized CMUT resonator in the feedback loop of a Colpitts oscillator, which consumes 0.76 mW, when operated continuously. Using our anodic-bonding based fabrication process, we fabricated 6-, 8-, and 15-channel prototype arrays with a standard deviation of 1% in the parallel resonant frequency (4.5 MHz) in a 7x9-mm^2 die area. We measured the response of three channels, one uncoated, one with a polyisobutylene (PIB) layer, and one with a polyvinyl alcohol (PVA) layer, to 20-ppm toluene vapor. Initial measurements show 1:13:37 ratio in the response of reference:PVA:PIB channels.**

Keywords*— *multi-channel; selectivity; volatile organic compounds; capacitive micromachined ultrasonic transducer; mass-loading;

I. Introduction

Capacitive micromachined ultrasonic transducers (CMUT) have emerged as a strong candidate for microelectromechanical resonant-chemical sensor systems in recent years [1]. One of the attractive features of using a CMUT-based sensor system is the ability to arrange and implement an array of CMUT elements on the same die area. CMUTs have a higher quality factor compared to cantilevers with similar active area and demonstrate robust operation because of several hundreds of cells connected in parallel. The organization of CMUTs in arrays with elements functionalized with various polymers enhances selectivity [2].

We envision to develop low-power, miniaturized, wearable sensors to monitor environmental pollutants continuously and correlate the findings with physiological measurements. This research is a part of the NSF Nanosystems Engineering Research Center (NERC) for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST). In our previous work [2] we demonstrated a single-channel, polyisobutylene (PIB)-functionalized, low-power gas sensor consuming 0.77 mW (when operated continuously) and achieving 10-ppb resolution for toluene in the 10–20 ppm concentration range. In this study we aim to show that multi-channel arrays with elements functionalized with various polymers could potentially enhance selectivity. Our target analytes are primarily volatile organic compounds (VOCs) that are emitted by a wide array of products from cleaning supplies to office equipment such as copiers, etc., and hence degrade the indoor air quality significantly.

Arrays of CMUTs are designed and fabricated using a novel technique of fabricating high-quality, vacuum-sealed CMUTs on insulating substrates [2]. Different designs included on the wafer result in devices with quality factors ranging from 200 to 600. This process is a novel and simple three-mask process of fabricating vacuum-sealed CMUTs on an insulating glass substrate. The use of the device layer of a silicon-on-insulator (SOI) wafer as the plate of the CMUT allows a good control over thickness and uniformity. Anodic bonding provides the benefit of a cost-effective and low-temperature process and the use of patterned bottom electrode minimizes the parasitic series resistance and parasitic shunt capacitance [2].

For initial testing we used three CMUT devices from a 6-element array and established preliminary results for multi-channel gas sensor applications. The electrical input impedances of the devices were characterized in air. Three of these six CMUT resonators were used along with single-stage tuned Colpitts oscillator circuits that were designed to operate near the parallel resonance of the CMUT. The average power consumption per channel is 0.76 mW when run continuously. The Allan deviation measurement shows a minimum short-term frequency noise of 3.24 Hz (3-σ) achieved at an averaging time of 130 ms. Sections III and IV elaborate on the sensor sensing mechanism and the design and implementation of the multi-channel sensor system. Initial test results are reported in Section V.

II. CMUT Configuration and Characterization

A. CMUT Configuration

Arrays of 6-, 8-, and 15- element CMUT devices have been fabricated using a technique based on anodic bonding [2]. The complete wafer after fabrication is shown in Fig. 1(a). The arrangement of the devices are as shown in Fig. 1(b). Each CMUT device structure is composed of a patterned, fixed bottom gold electrode deposited inside a sub-micron vacuum-sealed cavity. The top electrode comprises of a single-crystal silicon layer and a silicon-nitride layer that acts as the

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vibrating plate. The silicon-nitride layer acts as an insulating layer and prevents any electrical short between the top and bottom electrodes.

B. *CMUT Characterization*

The electrical input impedance of the CMUT devices are characterized in air using a network analyzer (Model E5061B, Agilent Technologies, Inc., Santa Clara, CA) with an internal DC supply available up to 40 V. To examine the uniformity in resonant frequency a 6-element die is used. The mean parallel resonant frequency of the six devices in the array used in this study is 4.487 MHz with a 3-σ deviation of 152.2 kHz (Fig. 2).

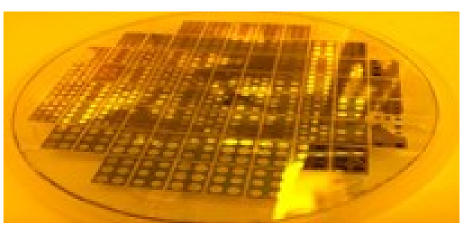
III. CMUT Operating Principle and Sensor Sensing Mechanism

A. *CMUT Operating Principle*

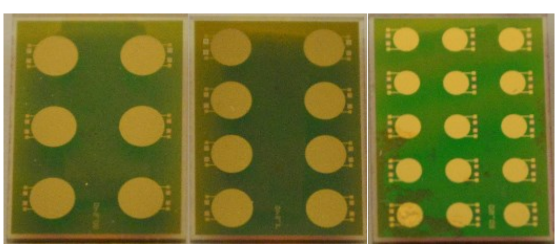
A CMUT resonator consists of a thin vibrating plate suspended over a vacuum gap. Multiple resonator cells are connected electrically in parallel to implement an larger area transducer with the desired motional impedance. When a DC bias is applied across the top and bottom electrodes of the CMUT the electrostatic force causes deflection in the top plate of the device. The mechanical restoring force of the top plate balances out the electrostatic force. The resonant frequency of the CMUT depends on the material properties of the plate and its dimensions.

B. *Sensing Mechanism*

The CMUT mechanical resonators are converted to gas sensors by coating the top plate of the device with a polymer selective to the target analytes. This process is generally referred to polymer functionalization. If a target analyte for which the CMUT is functionalized is present in close proximity it will be adsorbed by the polymer layer, which is equivalent to increase in the mass of the CMUT's plate. This increase in mass is referred as mass loading. Eqn 1 shows the relation between change in mass and the frequency shift.



(a)



(b)

Fig. 1: (a) Fully fabricated CMUT wafer. (b) 6-, 8-, and 15-element CMUT arrays after dicing the wafer. The area of each array is 9x7 mm^2.

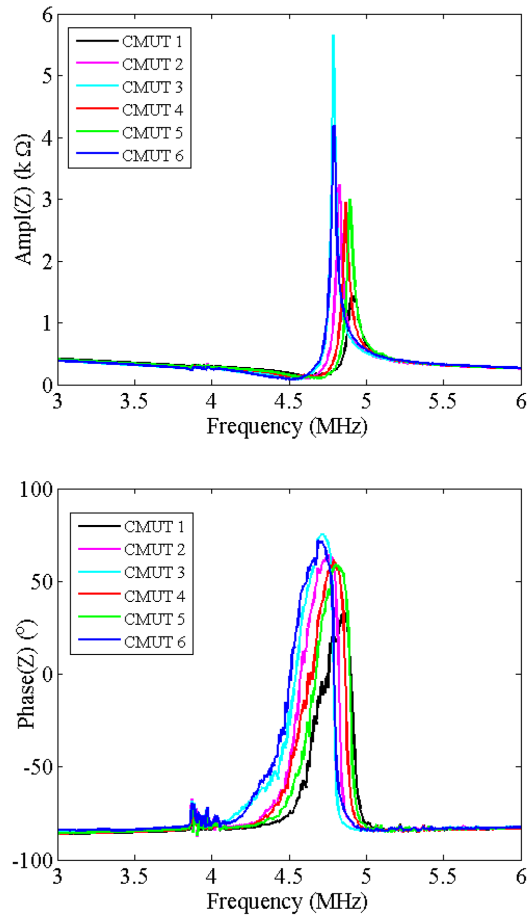


Fig. 2: Input impedance of the six CMUT resonators on a single die (V_{DC} = 17 V).

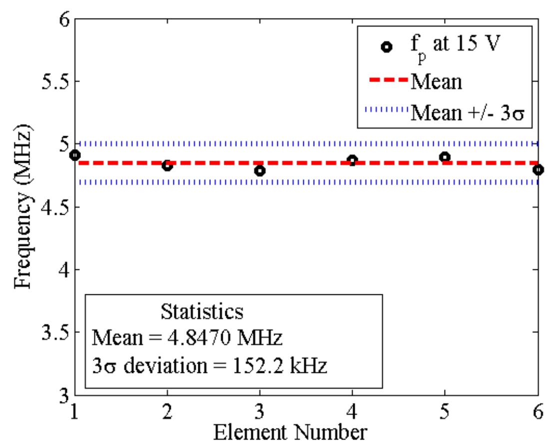


Fig. 3: Uniformity in the resonant frequencies of six CMUT resonators on a single die.

$$\partial m = -\frac{1}{2} \cdot \frac{f_0}{m} \cdot \partial f \quad (1)$$

In an array structure different elements can be functionalized with different polymer layers, ideally orthogonal to each other, so that selectivity to different chemical can be improved by employing classification algorithms such as the principal component analysis.

IV. DESIGN AND IMPLEMENTATION OF THE MULTI-CHANNEL SENSOR SYSTEM

The sensor system used for initial testing comprises of three CMUT devices, one functionalized using PIB, one functionalized using PVA and the third is kept unfunctionalized to use as a reference channel. Each CMUT is used as a frequency selective device in the feedback loop of a Colpitts oscillator designed with a single BJT amplifier. The output frequency from each oscillator is tracked by three frequency counters (Model 3230A, Agilent Technologies, Inc., Santa Clara, CA) and the data is recorded. The CMUTs are enclosed in a chamber 13.1 cm^3 volume with inlet and outlet pipes (0.635 cm diameter) for gas flow during testing (Fig. 4).

A. *Oscillator Design*

The complete schematic of the BJT-Colpitts oscillator designed to interface with the CMUT is shown in Fig. 5. Here C_1 and C_2 are the resonating capacitances. C_1 and C_2 were chosen to be same to minimize the g_m required for oscillation. This approach is taken as minimizing the power consumption is one of the most critical aspects of the presented system. Bias current is directly dependent on g_m for the BJT and given as $I_{bias} \approx \frac{g_m}{40}$. R_1 and R_{bias} are used to bias the oscillator for the desired DC operating point. The designed oscillator consumed 760 μW power with a 1.8 V supply and CMUT biased at 17 V DC. The oscillators exhibit an average of 3.24 Hz (3-σ) Allan deviation achieved at an averaging time of 130 ms (Fig. 6)

B. *CMUT Functionalization*

Three CMUT devices constitute the sensor system. Dilute solutions PIB (1 mg of PIB /mL of toluene) and PVA (1 mg of PVA/mL of DI water) were prepared. The CMUTs were drop coated with the polymer solutions using a handheld adjustable-volume (10 μL − 100 μL range) micro-pipette (Research Plus, Eppendorf AG, Hamburg, Germany) and the solvent was allowed to evaporate. The impedance of the devices were measured again after coating and there was no significant change before and after the coating.

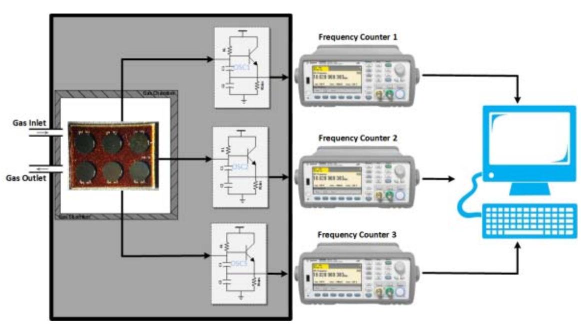


Fig. 4: CMUT resonators in the feedback loop of Colpitts oscillators. The CMUT die is enclosed in a chamber with an inlet and outlet for the flow of test gases. The frequency of oscillation is recorded.

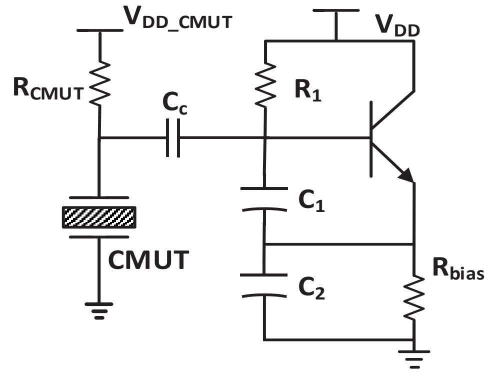


Fig. 5: Schematic of the Colpitts oscillator.

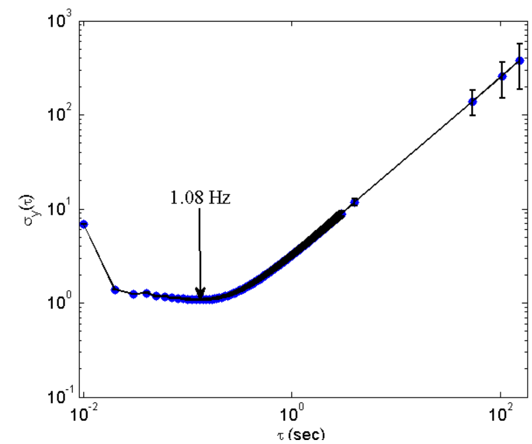


Fig. 6. Overlapped Allan deviation calculated using the data acquired by the frequency counter (Model 3230A, Agilent Technologies, Inc., Santa Clara, CA) with a gate time of 2 ms.

V. CHEMICAL TEST SETUP AND RESULTS

A. *Generation of Trace Gases*

National Institute of Standards and Technology (NIST) standard trace concentration level of VOCs is generated for the chemical tests using a calibration vapor generator (Model OVG-4, Owlstone Inc., Norwalk, CT). This system uses permeation tube technology to generate trace gases. Permeation tubes are polymer tubes, generally PTFE, of certain lengths, with analytes of interest filled in and crimped at both ends. The tube is then placed in the OVG-4 system's oven and clean air is flowed constantly into the chamber. The clean air is generated using a zero air generator (Model ZAG–6, BCAS Limited, Wallingford Oxon, UK). The oven temperature is kept constant at a certain level and with the flow of clean air from one end and a high temperature in the oven, the analytes from the tube diffuse through the permeation tube walls and analyte stream is obtained from another end. VOC gases are generated and the permeation rate

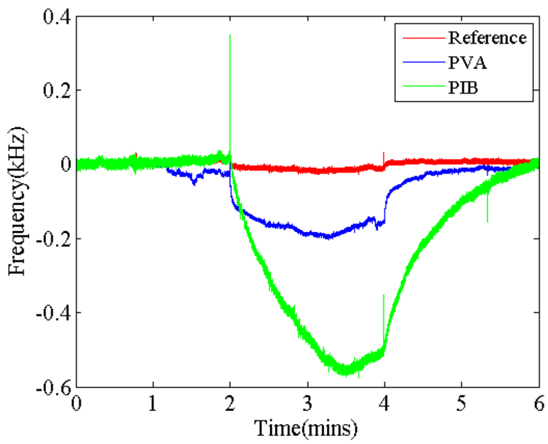


Fig. 7: Initial test result showing higher selectivity to toluene by the PIB coated channel. Toluene is flowed between 2-4 minutes.

calibrated at first. Once permeation rates for a certain VOC is determined, the concentration of analytes can be calculated. The concentration can also be varied by changing the air flow rate and temperature of the oven.

B. Chemical Test Results

The initial test was performed with the 3-channel sensor. Measured response of three channels, one uncoated, one with a polyisobutylene (PIB) layer, and one with a polyvinyl alcohol (PVA) layer, to 20-ppm toluene vapor show 1:13:37 ratio in the response of reference:PVA:PIB channels (Fig. 7). Further experiments with wider range of concentration and different analytes are in progress.

VI. Conclusion

In this paper we presented a CMUT array design for implementing a multi-channel sensor system for improved selectivity in sensing VOCs. The initial data was obtained using a three-channel system based on discrete electronic circuits and bench-top frequency counters. Two of the three resonators were functionalized with PIB and PVA and one channel was left unfunctionalized as a reference. With the presented initial results we demonstrated that we could design and fabricate uniform resonator arrays and functionalize adjacent channels with different polymers. We also demonstrated low-power interface circuits. Our current efforts are on increasing the number of functionalized channels and test the system with different analytes with a wider range of concentration.

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