A Battery-Operated Wireless Multichannel Gas Sensor System Based on a Capacitive Micromachined Ultrasonic Transducer (CMUT) Array

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***Abstract*—This paper reports on the design and implementation of a complete battery-operated wireless system for a mechanically resonant gas sensor based on a capacitive micromachined ultrasonic transducer (CMUT) array. A custom-designed front-end integrated circuit (IC) with eight inputs and a serial peripheral interface (SPI) was tightly integrated with a CMUT array. The power consumption of the front-end is 10 µW with a duty cycle of 1:60 corresponding to 1-s measurement time every minute. For the completeness of the system, a power management unit (PMU) was designed and interfaced with the described custom IC along with a wireless module. For multichannel operation, time-division multiplexing was adopted to minimize power consumption and prevent potential frequency locking between different channels. Multichannel wireless data acquisition with the described system was demonstrated by loading unfunctionalized sensor channels with humidity in human breath.**

Keywords—capacitive micromachined ultrasonic transducer; wireless; multichannel; integrated circuit; battery; resonator; oscillator;

I. INTRODUCTION

Volatile organic compounds (VOCs) represent a large group of environmental pollutants with short- and long-term adverse health effects. VOCs are numerous and ubiquitous. Their concentration is usually low in the environment and therefore symptoms of health problems due to VOC exposure develop slowly. In order to assess the effects of harmful VOCs on health, it is necessary to monitor VOC concentrations continuously and correlate individual exposure levels with the physiological state. As a result much research in recent years has focused on the development of wearable low-power sensor systems for continuous monitoring of environment and health in correlation with each other [1].

Capacitive micromachined ultrasonic transducers (CMUTs) have been of great interest as a potential resonant mass-loading sensor for VOCs due to ease of implementation of an array of resonators on a single die to enable multichannel detection for achieving high specificity. In previous work we implemented oscillators with discrete components for multichannel sensors and demonstrated VOC sensing in the laboratory [2]. IC implementation of the interface circuits is desired to minimize the form factor and power consumption of the overall sensor system. A 4-channel oscillator IC for a CMUT array was demonstrated earlier [4]. This IC had all channels active at the same time and therefore consumed high power and suffered from frequency locking between different channels. Furthermore this IC did not include digital frequency counters and required bench-top instruments for a digital readout. Recently, we have demonstrated a single-channel IC with digital readout for interfacing a single-channel CMUT as a resonant gas sensor [3].

In this study, we developed a CMUT-based battery-operated wireless multichannel sensor system designed specifically as a wearable personal environmental monitor. The complete system demonstration was achieved by integrating the custom-designed low-power multichannel front-end IC, a multichannel CMUT array, a board-level power management unit for generating bias voltages, and a commercial microcontroller with a Bluetooth low energy connectivity.

II. CMUT RESONANT SENSOR AND FRONT-END INTEGRATED CIRCUIT

A. CMUT array

A 6-element CMUT array [2], which was attached and wire bonded to a chip carrier (PLCC-44, Kyocera America, Inc, San Diego, CA), was used as a multichannel resonant gas sensor [Fig. 1 (a)]. Each resonant CMUT in the array is formed by connecting multiple circular resonator cells in parallel to achieve a low motional impedance and a large sensing area [Fig. 1 (b)].

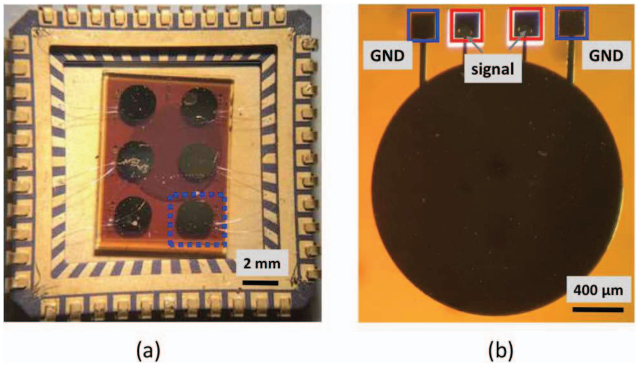

Fig. 1. (a) A 6-element CMUT array. (b) A single CMUT element.

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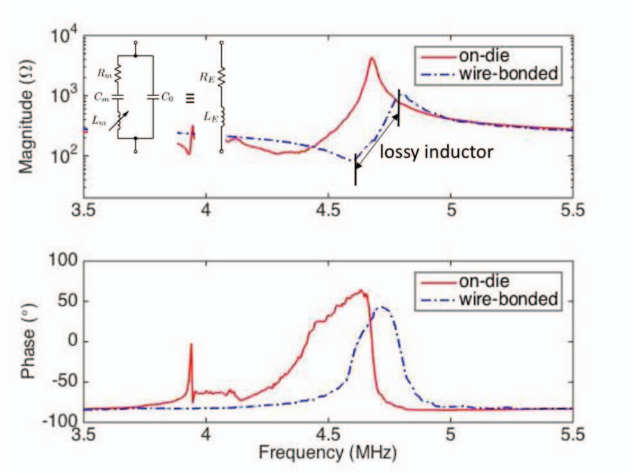

Fig. 2. Measured input impedance of a CMUT at a bias voltage of 13.5 V before (on-die) and after wire-bonding (inset: equivalent circuit model near parallel resonance).

The top electrodes (GND) were wire bonded to a common ground. The bottom electrode (signal) of each sensor was connected to a high-voltage (HV) DC bias through a 1-MΩ resistor, and AC-coupled to an oscillator.

A single circular resonator cell can be regarded as a mechanical resonator with a thin vibrating plate over a vacuum gap. The CMUT resonator is used as a gas sensor by coating the top plate with a polymer selective to a target gas. This process is generally called polymer functionalization. When the polymer adsorbs gas molecules, the mass of the CMUT's vibrating plate increases and hence the resonant frequency decreases. By monitoring the frequency changes concentration of the target gas in the ambient atmosphere can be measured. Furthermore, in an array, specificity can be improved by functionalizing the elements with different polymers and employing pattern recognition during data processing.

B. *Characterization of the CMUT resonator*

A CMUT resonator generally oscillates near the parallel resonance region where the resonator can be modeled as a lossy inductor, phase and amplitude of which increase with increasing frequency (Fig. 2). An oscillator must provide negative resistance to compensate for the loss of the resonator to sustain the oscillation.

Although our previous work showed that the resonant frequencies of CMUT resonators on the same die were adequately uniform [2], the characteristics of a CMUT would change to a certain extent at different stages of implementation such as wire bonding (Fig. 2) and polymer functionalization. In particular, any parasitic shunt capacitance will reduce the effective negative resistance provided by an oscillator. In order to comply with these variations, the inverter-based oscillator design [3] was used throughout this study since it provides robust startup and higher negative resistance due to its higher closed-loop gain compared to the single-stage Colpitts oscillator design.

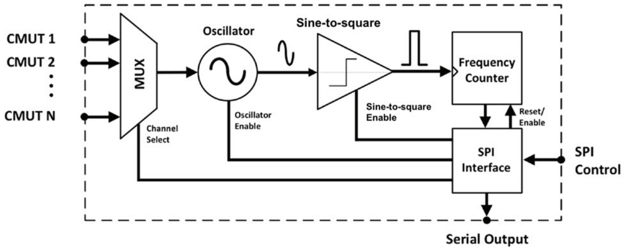

Fig. 3. Schematic block diagram of the second-generation integrated circuit.

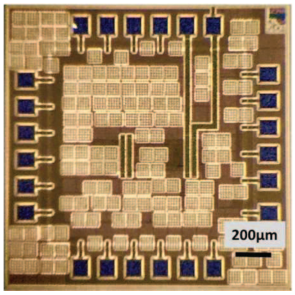

Fig. 4. Die photograph of the second-generation integrated circuit.

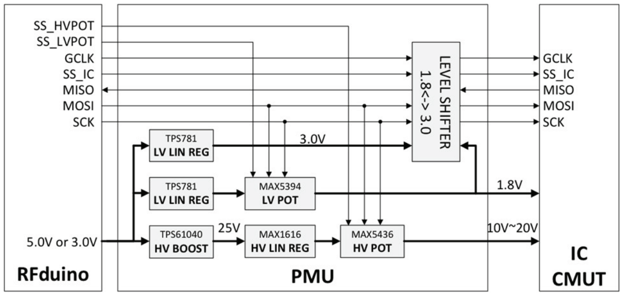

Fig. 5. Schematic block diagram of the complete system.

C. *The front-end integrated circuit*

The front-end IC used in this work was an enhanced version of the IC developed in our previous work [3]. Eight analog-input pins and a multiplexer were added, so allowing the IC to accept multiple inputs from a CMUT array (Fig. 3). The Serial Peripheral Interface (SPI) block was embedded to provide a standard way of communication with a microcontroller. The inclusion of the SPI also reduced the number of pins for controls and simplified the programming for generating the control signals. The IC was fabricated in a 0.18-µm BiCMOS process (Fig. 4). The power consumption was 10 µW with a 1.8-V core supply, which is identical to that of the first-generation IC with a duty cycle of 1:60 corresponding to 1-s measurement time every minute. The oscillator showed the lowest modified Allan deviation of 0.95 Hz (1σ) at an averaging time of 0.25 s, which is comparable to that of a Colpitts oscillator implemented using discrete components [2] and low enough to meet the limit of detection (LOD) for most VOCs.

III. IMPLEMENTATION OF THE WIRELESS MULTICHANNEL SENSING SYSTEM

A. *Power management unit (PMU)*

A programmable on-board power management unit (PMU) was implemented to provide a HV bias for CMUT sensors and

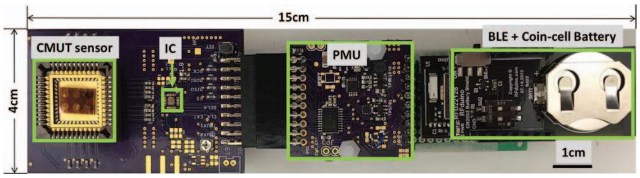

Fig. 6. The coin-cell battery operated wireless sensing prototype.

1.8-V bias voltage for the IC (Fig. 5). The high-voltage boost converter (HV boost) generates 25 V from a battery followed by the high-voltage linear regulator (HV LIN REG) that offers a configurable output voltage between 10 V and 20 V in conjunction with a high-voltage 128-tap digital potentiometer via SPI. The PMU also includes bidirectional level shifters that translate voltage levels between the IC and a microcontroller.

B. *Complete wireless sensing system*

To offer a means of controlling the front-end IC and transmitting the acquired data wirelessly, an Arduino compatible and Bluetooth low energy (BLE) enabled microcontroller (RFduino, RF Digital Corporation, Hermosa Beach, CA) was employed. A battery-powered prototype was constructed as a complete wireless sensing system (Fig. 6). A control software in a host computer was written in Python using BlueZ, a Bluetooth protocol stack for Linux systems.

IV. SYSTEM OPERATIONS AND RESULTS

A. *System operations*

The wireless sensor module is controllable wirelessly by a Python script on the host computer. The host script sends gate time and register values for the HV regulator and sensor channel selection wirelessly. Then, the microcontroller controls the HV regulator and the front-end IC via SPI. A gate time is generated by the internal clock of the microcontroller and sent to the IC via a general purpose input/output (GPIO) pin in order to be used for counting the frequency. When the frequency counting by the IC is complete, the frequency counts are sent to the microcontroller via SPI, then to the host wirelessly. The same procedure is repeated on all selected channels. A wait time of 20 ms is inserted for starting data acquisition after switching channels to ensure a stable HV DC bias and allow the frequency to stabilize after channel switching as shown in Fig. 7. The acquired data are recorded in text files and displayed on the screen in real time. By adopting such a time-division multiplexing approach potential frequency locking between different channels is avoided and the overall power consumption is minimized.

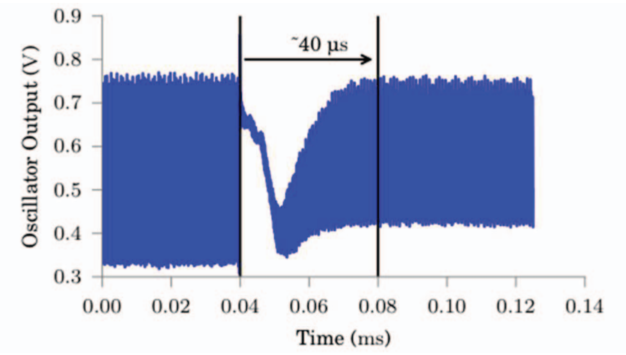

Fig. 7. Settling time required for switching between channels.

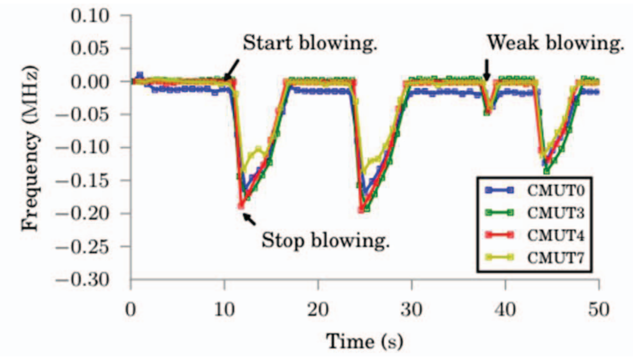

Fig. 8. Demonstration of multichannel sensing showing frequency shifts with repeated blowing over a sensor array.

B. *Multichannel data acquisition results*

In the previous study, the performance of the circuit building blocks implemented in the first-generation IC was characterized by interfacing the IC with a single-channel CMUT [3]. In this study, wireless multichannel data acquisition using the second-generation IC was demonstrated using a 6-element unfunctionalized CMUT array. For demonstrating the system functionality the frequency was modulated by blowing on the sensor to load the sensor surface by condensation of humidity in the exhaled breath. Four channels were selected for data acquisition. A gate time of 0.2 s was used for each channel. Four selected channels were cycled sequentially. It is observed that the frequency on all channels shifted down when one blew on the sensor and the baseline was recovered after the blowing was stopped (Fig. 8).

V. CONCLUSION

A battery-operated wireless prototype for a multichannel CMUT based gas sensor system was developed. An enhanced version of the IC with multichannel inputs and SPI was tightly integrated with a CMUT array. A PMU provides programmable power supplies to the system. RFduino is used for system control and wireless communication. Multichannel wireless data acquisition is demonstrated by using humidity as the input to the sensor array. Future work will focus on testing the system with a polymer functionalized CMUT array for detecting various concentrations of different analytes and employing custom low-power system-on-chip and radio on the backend.

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