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Improved Interface Circuits for CMUT Chemical Sensors

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***Abstract*—Capacitive Micromachined Ultrasonic Transducer (CMUT) chemical sensors have demonstrated outstanding sensitivity for chemical sensing in air. In order to achieve good low limit of detection and good sensor reliability, attention must be paid to the interface circuits. In this work, we demonstrate how a transistor-based oscillator circuit can be used to achieve low noise, small size and low power consumption for CMUT chemical sensor arrays. We show how to optimize these circuits, and show how they can be enabled and disabled to allow multiplexing in time.**

***Index Terms*—CMUT, Chemical Sensor, Oscillator Circuit, Allan Deviation**

I. Introduction

Capacitive Micromachined Ultrasonic Transducer (CMUT) based chemical sensors have been demonstrated to have excellent sensitivity for gas-phase chemical sensing [1]. Their small size and batch fabrication makes them a good candidate for low-cost, miniaturized gas sensing, and their multi-cell structure allows low noise and thus lower limit of detection compared to other types of gravimetric sensors [2].

The limit of detection of the sensor is determined both by the sensitivity of the sensor and the noise. It is therefore important to optimize both the sensor design and the interface electronics in order to achieve the best possible performance. In addition to having low noise, the readout circuits should not consume too much power so that they are suitable for miniaturized sensors that can be deployed in large numbers. Finally, circuits should be suitable for multi-sensor implementation so that arrays of sensors can be used to distinguish different chemicals or scents [3].

Much past work on CMUT chemical sensors has used op-amp based oscillators. Transistor-based oscillators have been demonstrated in a single-channel implementation with excellent noise performance [4], and with much worse noise performance in a two-channel implementation [5]. We have demonstrated a multi-channel, transistor-based oscillator with noise performance matching the previous best result. We describe how the circuit can be optimized to work well for CMUTs with a range of properties. The circuit works well with a wide range of CMUT characteristics without any modification. The circuit also has a disable mechanism, allowing time-multiplexing.

II. Methods

CMUT chemical sensors use a gravimetric sensing mechanism. A schematic cross-section of the sensor is shown in Fig. 1a. The top plate of the sensor is coated with a functionalization layer which reversibly absorbs target chemicals in the air. The mass of the the absorbed chemical shifts the resonance frequency of the plate. A single sensor consists of many individual CMUT cells connected in parallel to reduce noise. Multiple sensors can be fabricated on the same chip. An image of a 10-sensor chip is shown in Fig. 1c.

The sensor readout is electrical. The substrate of the chip is shared between sensors and is grounded. Voltages are applied to the top plate. The frequency of a sensor can be measured by placing it in an oscillator circuit that oscillates at the resonance frequency of the device and measuring the resulting signal with a frequency counter.

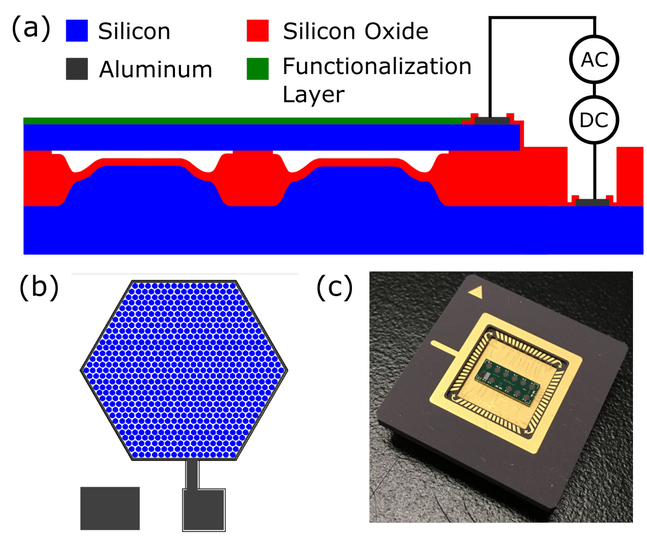

Fig. 1. (a) CMUT chemical sensor cross-section. (b) Layout of a single chemical sensor with 721 cells. (c) A CMUT chemical sensor chip with 10 chemical sensors.

The sensors used in this work have been described previously [6]. Each sensor consists of 721 cells with 9 μm radius. The cells are arranged in a hexagon, as shown in Fig. 1c. They have a frequency of 30 MHz and collapse voltage of 65 V.

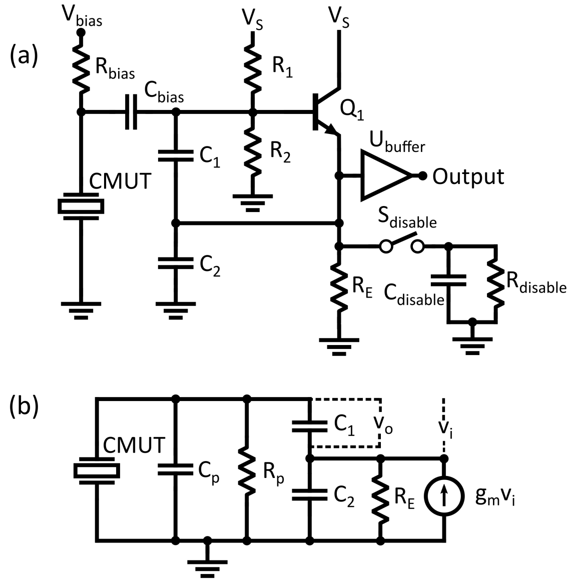

Fig. 2. (a) Schematic of the oscillator circuit. (b) Small-signal equivalent circuit model of the oscillator circuit.

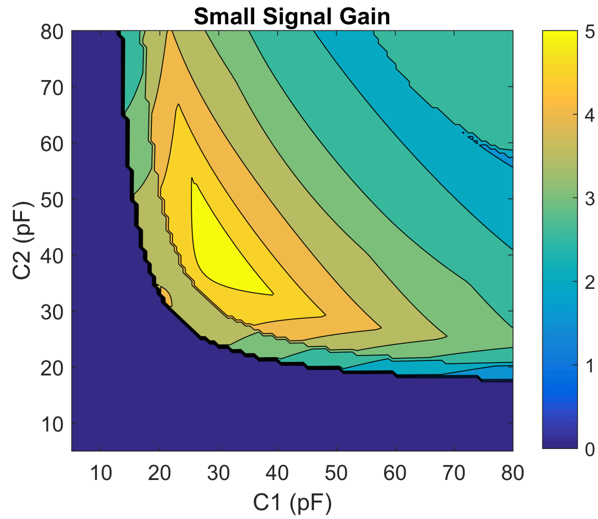

Fig. 3. Small-signal gain at the operating frequency as a function of C1 and C2.

The oscillator circuit topology is shown in Fig. 2a. It is based on the design of Santos and Meyer [7], and similar to that used by Lee et al. [4]. The CMUT chemical sensors in this work share a common ground, so one side of the sensor must be grounded in the circuit. This rules out some oscillator circuit topologies like the Pierce oscillator.

The CMUT is biased and AC coupled to the circuit through C_{bias}. R_1 and R_2 set the DC base voltage of the transistor. The R_E sets the transistor bias current and thus the transimpedance. The feedback comes through C_1 and C_2. The circuit output is taken at the emitter through a buffer.

A small-signal open-loop model is shown in Fig. 2b, including parasitic capacitance Cp. The voltage input is v_i. It controls the current source. The output is v_o. The CMUT is AC coupled to the circuit through C_{bias}, which has low impedance at the oscillation frequency. The CMUT impedance is measured and the measurement data is used in the model.

The small-signal equivalent circuit model can be used to choose the components values. The Barkhausen stability criterion requires a gain of 1 and phase shift of $2\pi n$ around the loop. In practice, the small-signal gain should be greater than one. It is then limited to 1 by the non-linearity of the transistor. The operating frequency of the circuit is found by finding the point with zero phase shift and gain greater than 1. Fig. 3 shows the gain at the operating frequency as a function of C_1 and C_2 for a particular CMUT at a particular bias voltage with a particular transimpedance. The measured impedance of the CMUT is used in the model. Combinations of C_1 and C_2 that do not allow oscillation are plotted as having zero gain.

We used the small signal model to identify the range of C_1, C_2, and R_E that can produce oscillations for a variety of measured CMUT impedances at a variety of DC bias voltages. C_1 = 56 pF, C_2 = 62 pF, and R_E = 1.5 kΩ were chosen. In this way, we ensured that the design was tolerant of device-to-device variation and differences in bias voltage.

One challenge for CMUT chemical sensors on the same chip is that they can lock together and oscillate at the same frequency. One way to avoid this is to offset the bias voltages so that the sensors operate at different frequencies [3]. Another approach is to multiplex the sensors in time. This eliminates the need for offset bias voltages and eliminates noise challenges from crosstalk between the sensors. However, the oscillator circuits must start up extremely reliably and must not require a long time to settle at the correct frequency.

To enable rapid turn-on and shut-down of the oscillators, we added a disable switch, shown in Fig. 2b. When the switch is closed, the capacitor $C_{disable}$ adds a large amount of additional capacitance in parallel with C_2, reducing the gain so that the circuit does not oscillate. The resistor $R_{disable}$ discharges $C_{disable}$ when the switch is open and is large compared to R_E. This scheme keeps the bias currents through the circuit constant whether the circuit is on or off to reduce start-up transients.

III. Results

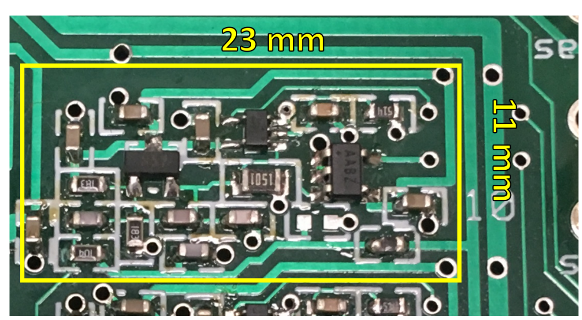

Fig. 4. Image of a single oscillator circuit.

Circuits were constructed on printed circuit boards using discrete components. An image of a single oscillator circuit is shown in Fig. 4 with approximate dimensions. The circuit has a smaller component count and smaller size than is required for op amp-based approaches. The power consumption is also much lower. The oscillator circuit consumes 18 mW, which is dominated by the buffer (11 mW).

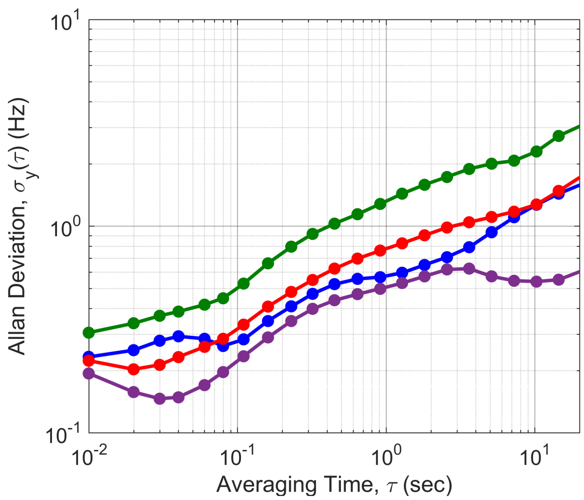

Fig. 5. Allan deviation of four different chemical sensors on a chip.

Fig. 5 shows the overlapped Allan deviation measured for 4 different sensors on the same chip using this oscillator circuit design. The Allan deviation is a standard way of characterizing frequency stability as a function of the sampling period [8]. Minimum Allan deviation is a commonly-used benchmark for resonator performance. The Allan deviation is meant to characterize noise and not drift, for example temperature drift. So, we subtract drift from the frequency vs. time data with a linear fit.

All 4 sensors perform well in the circuit, with <1 Hz minimum Allan deviation. The best device shows a minimum Allan deviation of 0.15 Hz at 31.365 MHz, or 4.7 ppb. This matched the lowest minimum Allan deviation that has been measured for a CMUT chemical sensor that we are aware of [4]. The other sensors show similar performance.

The disable switch was able to reliably enable and disable the oscillator. Fig. 6 shows the change in frequency vs. time of the four sensors in Fig. 5 immediately after enable the oscillator. Time zero is the time when the frequency counter first detects an input signal. The circuit reaches its oscillation frequency extremely quickly and does not show a protracted warm-up towards its equilibrium frequency.

To show the ability of this circuit to be used with a time multiplexing approach, we measured the frequency of four sensors over 10 minutes, turning them on one after another in sequence. A frequency value was recorded every 2.5 seconds for each sample. The results are shown in Fig. 7. The top plot shows the absolute frequencies while the bottom plot shows the change in frequency.

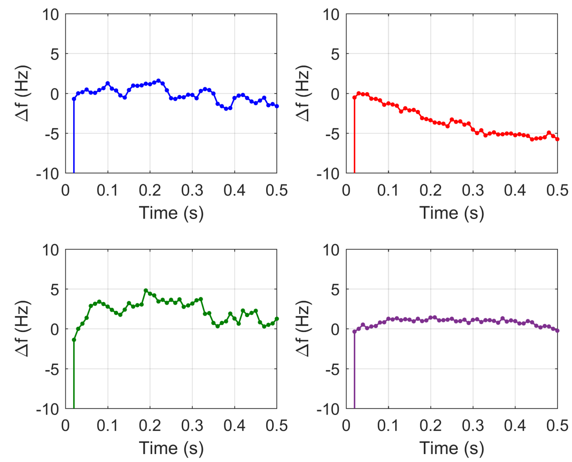

Fig. 6. Frequency vs. time immediately after enabling for four oscillators.

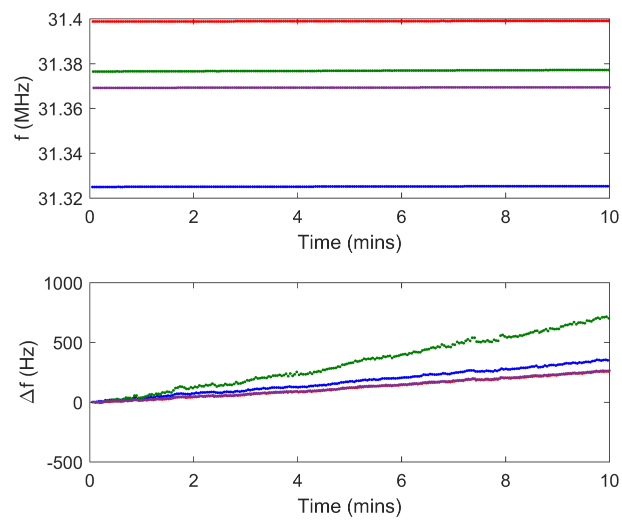

Fig. 7. Frequency vs. time of four chemical sensors measured simulateously by multiplexing in time

IV. Conclusion

Using a transistor-based oscillator circuit can bring significant improvements for CMUT chemical sensors. Excellent noise performance can be achieved - this work with a 30 MHz sensor and previous work with a 42.7 MHz sensor [4] both achieved a 4.7 ppb minimum Allan deviation, which is lower than any that has been achieved with op amp-based circuits. The circuit can be optimized to give reliable performance across devices and bias voltages. We have also shown how the circuit can be rapidly enabled and disable to prevent interference with other sensors. This allows multiplexing of the sensors in time, rather than just by frequency. Or, a combined approach could be used were a subset of sensors are turned on at given time. Finally, while this oscillator circuit topology has shown great utility for CMUT chemical sensors, it could also be applied to other types of resonant sensors.

Acknowledgment

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