Preparation and Simulation of a SAW/Capacitance Sensor

Thisara S. C. Walpita, and Fred Lacy

***Abstract*—Reducing the size of large laboratory based equipment and combining various sensors on one chip would be beneficial. Surface Acoustic Wave (SAW) and capacitance measurements have broad applications for electronic sensors, radar, and chemistry. Mass analyzing of molecules is one of the parameters required to identify and categorize chemicals or materials. The proposed method of using a SAW and capacitance sensor is a more cost-effective system that can be used at the millimeter scale as an electrochemical sensor. The electrical signals from this sensor are expected to be generated according to the molecular mass of the analyte. The steps necessary to fabricate this sensor along with computer simulations are presented to provide evidence of the feasibility of this sensor.**

***Index Terms*—chemical sensor, closed-loop oscillation, interdigital transducer (IDT), LabVIEW simulation**

I. Introduction

Measurements are an important part of every branch of science and engineering. Measurements based on Surface Acoustic Waves (SAW) and capacitance have broad applications and are used in fields such as communication systems, radar, and chemistry. Designing sensors for these measurements requires understanding the underlying operating mechanism of the materials and/or components. Moreover, miniaturizing large laboratory based equipment requires understanding how the sensor will function on a micro-scale and/or nano-scale. Additionally, when sensors are integrated onto one chip (or substrate), interference can occur. Therefore, it is important to characterize the sensor chip to ensure it will function as intended.

Determining molecular mass is a measurement that is required in order to identify an unknown chemical material. Mass determination has applications to fields such as material science and engineering [1], chemistry [2], biology [3], biochemistry [4], and toxicology [5]. The use of mass spectrometry was developed centuries ago to identify this important parameter of materials and molecules. However, mass spectrometers are typically large laboratory based systems that are not portable as well as very expensive. Thus, it is desirable to develop a miniaturized or portable mass measurement device that is relatively inexpensive.

To develop a miniaturized and portable mass spectrometer, a microfabricated sensor is proposed to measure molecular mass. This sensor is based on surface acoustic waves (SAW) and capacitance measurements. The SAW sensor will give a proportional electrical signal according to the mass change (on the order of 10^{-9}g) on the SAW sensor surface [6]. The capacitance sensor will give a proportional signal according to a change in concentration between the parallel plates of the capacitor [7, 8]. These two measurements will be used to determine the mass of molecules by using mathematical equations.

The sensor is an electro-chemical device which will produce an electrical output signal according to changes on the sensor surface. The sensor will detect changes on the sensor surface and its output will be a change in oscillation frequency, phase shift, or amplitude change. This will depends on the type of SAW sensor [9]. Frequency change with respect to time has been simulated in this experiment.

II. Sensor Description and Operation

The proposed sensor device, as shown in Figure 1, is a combination of two separate sensors on the same substrate. This SAW / capacitance sensor will be fabricated on a millimeter scale piezoelectric substrate (14mm x 7mm). The fabrication of each sensor will be on separate layers of the device which will be on the order of micrometer thickness. It is noted that the SAW sensor will be a pre-designed and tested sensor. The SAW sensor design information has been obtained from published information [10]).

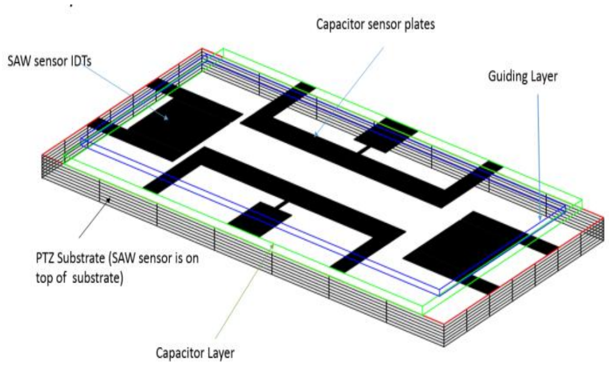

Fig. 1. Diagram of the SAW/Capacitance sensor.

The electrode capacitance sensor layer will be the second layer of the sensor and the fist layer will serve as a

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protection and insulation layer for the electrodes of the capacitor. There will be a separation layer under the capacitance sensor layer. The last layer will be SAW sensor layer which will be fabricated on top of the piezoelectric substrate. It is noted that the SH-SAW [11] sensor will convert to a LOVE wave sensor [12] because of the additional polymer layers. This increases the sensitivity and durability of sensor [9, 13-16]. A diagram of the sensor device is shown in Figure 1.

The surface waves from the SAW portion of the sensor are generated by interdigital transducer (IDT) electrodes [12]. The SAW sensor and the capacitance sensor will work with a closed loop oscillation system. The oscillator frequencies for each sensor will be monitored separately. The change in frequency of the SAW sensor will be proportional to the change in mass on the surface of the device [10, 16]. Additionally, when molecules are on the surface of the sensor, they will affect the permittivity (or dielectric constant) between the capacitor plates of the sensor, as a result, the capacitance changes [17]. This monitored data will then go through a derived mathematical equation to obtain the molecular mass of the unknown compound.

III. PROCEDURE

A. *Fabrication*

In order to make the SAW sensor more sensitive to changes in mass on its surface [9, 12], the sensor will be fabricated on a lead zirconate titanate (PZT) substrate. This PZT substrate has a special crystal cut that will yield shear horizontal surface waves [10, 18]. This crystal is Lithium Tantalite ($LiTaO_3$) with 36^0 – rotated Y – cut.

Fabrication of this sensor will involve standard clean room LIGA processing. The sensor fabrication will involve 4 photolithography masks to complete the different layers required to incorporate a SAW and capacitance sensor into one device.

The first layer will contain SAW IDT electrodes. These electrodes will have a width of 10µm, a spacing of 10µm apart, and a height or thickness of 0.3µm. There will be 100 parallel IDTs for the input and output electrodes.

The second layer will be the wave guiding layer for the SAW sensor. It will contain a layer of parylene of 1µm thickness [10, 19]. This material adheres well with the substrate and is good for guiding surface waves.

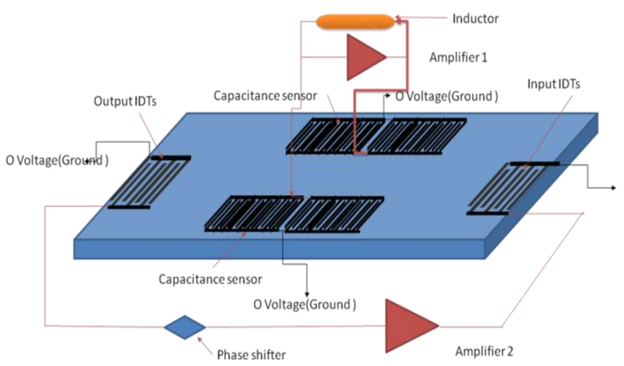

Fig. 2. Sensor connected to electronic circuitry to detect and measure molecules on the surface.

The third layer will contain the capacitance sensor. It will contain gold plates of width 10µm, a spacing of 10µm, and a height or thickness of 9µm. There will be 167 parallel plates for this capacitor on the third layer [20].

The fourth layer is a protective layer that will insulate and protect the capacitance and SAW sensors.

B. *Computer Simulation*

A computer simulation program has been implemented to characterize the performance of the SAW / capacitance sensor. This was performed in LabVIEW which is a programming environment in which virtual instruments and devices can be designed and simulated to represent a real system. LabVIEW is a graphical programming language supported by National Instrument.

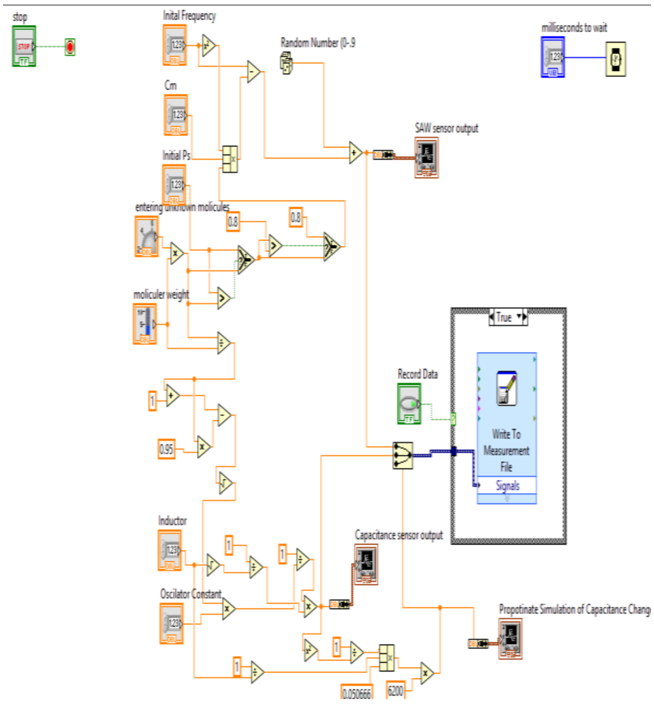

Fig. 3. LabVIEW block diagram used to simulate the SAW and Capacitance sensor.

As shown in Figure 2, the SAW and capacitor sensors are components of oscillator circuits. These circuits will be used to measure the mass and concentration change of an analyte on the surface of the sensor. Amplifier 1 is a component of a Colpitts oscillator [21] in which the capacitance of the sensor will determine the frequency of oscillation. As molecules are placed on the surface, they alter the capacitance of the device which alters the frequency of oscillation. Amplifier 2 will amplify the SAW signal to get a steady signal output of the SAW sensor after oscillation. Amplifier 2 and the phase shifter for the SAW sensor functions to provide a feedback oscillation loop. This phase shifter craters 180 degree phase shift.

The computer program constructed in LabVIEW will simulate this device as well as the external components that are used (and needed) in order for the device to function properly. Components were constructed in LabVIEW as shown in Figure 3. The block diagram is shown in this

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figure. Particle concentration and molecular mass (of each particle) are the two variables for the simulation.

IV. Results

A. *Preface*

This display in Figure 4 shows the frequency of the SAW sensor oscillator with the time. The initial frequency (initial stable frequency of the SAW sensor) needs to stabilize before recording data. As the surface mass or the concentration is varied, the output signal changes as well.

The capacitance change due to concentration change is relatively low (10^{-9} or 10^{-12} F level) [22]. Again, the change in oscillation frequency of a Colpitts oscillator is measured because it is difficult to measure capacitance change directly. Measuring a signal such as voltage or current is needed. Through signal frequency measurements, the plot in Figure 4 shows a proportionate signal for the actual capacitance change of the sensor. Figure 4 also shows the response of the SAW sensor per unit mass load on the surface. This is shown using a nanogram scale.

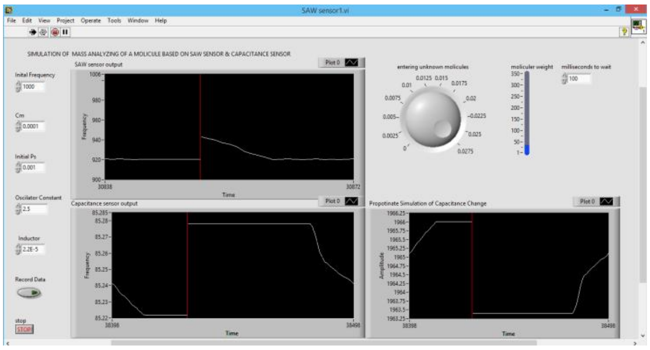

Fig. 4. LabVIEW display of the sensor response.

There are two parameters that are recorded to get the final answer. The frequency of the SAW sensor with respect to time and the capacitance (through measured frequency) with respect to time are recorded. This corresponds to mass change with respect to time and concentration change with respect to time, respectively.

A plot of frequency change vs. capacitance change (which is equivalently graphed as mass change vs. concentration) can be created by analyzing the sensor data. A plot is shown in Figure 5. The plot of mass change vs. concentration can be explained mathematically as follows

$$\frac{\Delta mass}{concentration} = M \qquad (1)$$

This implies that the slope of equation (1) explains the graph in Figure 5 and expresses a proportional or linear relationship with molecular mass.

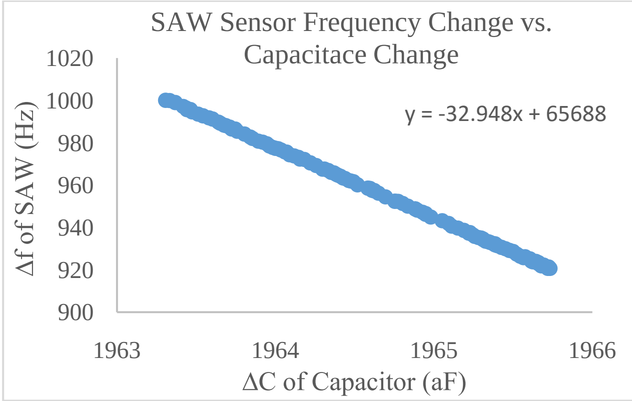

Fig. 5. Typical graph of frequency change (mass) as a function of capacitance change (concentration).

B. *Simulation for Water Detection*

The analytic for detecting water needs to be pasted on top of the sensor surface (a special experiment setup is required). The sensor system should be at rest for frequency stabilization. For the described SAW sensor and capacitance sensor, the oscillation frequencies change mathematically according to changes in mass and concentration, respectively. Figure 6 shows results that are obtained after analyzing the corresponding data.

This graph displays concentration change vs. mass difference. According to equation (1), the slope of the graph should be proportional to the weight of the molecules on the surface of the sensor. The absolute value of the slope is 18.065. The grams per mole for H_2O is approximately 18

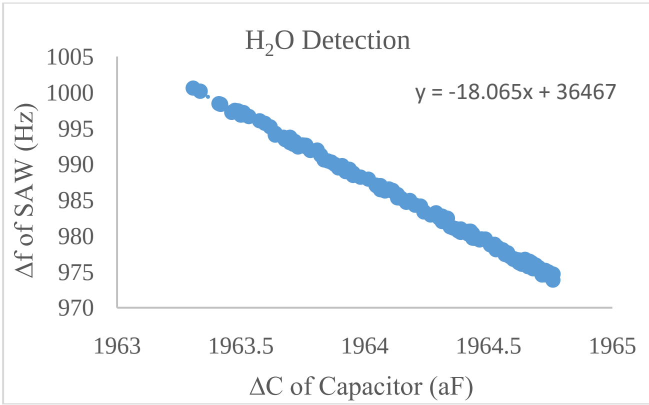

Fig. 6. Frequency change (mass) vs. capacitance change (concentration) for H_2O.

C. *Simulation for Sulfur Dioxide Detection*

Figure 7 shows results that are obtained after analyzing the corresponding data for Sulfur Dioxide (SO_2). This graph displays concentration change vs. mass difference. According to Eq. (1), the slope of the graph should be proportionate to the weight of the molecule on the surface of the sensor. The absolute value of the slope is 64.475. The grams per mole for SO_2 is approximately 64.

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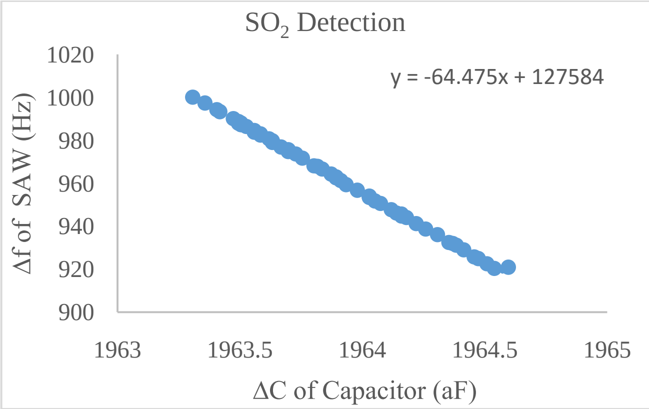

Fig. 7. Frequency change (mass) vs. capacitance change (concentration) for SO_2.

D. Simulation for Oxygen Detection

Finally, Figure 8 shows results that are obtained after analyzing the corresponding data for Oxygen (O_2). This graph displays concentration change vs. mass difference. According to Eq. (1), the slope of the graph should be proportionate to the weight of the molecule on the surface of the sensor. The absolute value of the slope is 32.895. The grams per mole for O_2 is approximately 32.

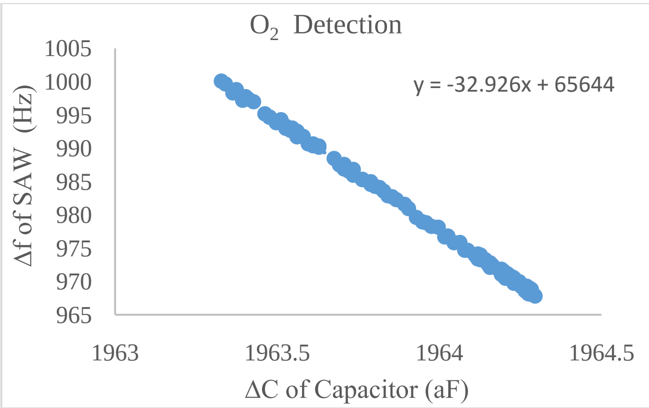

Fig. 8. Frequency change (mass) vs. capacitance change (concentration) for O_2.

V. Discussion and Conclusion

This device which will incorporate two different sensors onto one chip or substrate has been characterized through simulations. The simulations indicate that the device will function as anticipated. Furthermore, the fabrication process is understood, so upon fabrication of this novel sensor, the results should resemble the simulated results.

There are many references for detecting small mass changes by SAW sensors. The simulation results are consistent with the measurement values that would be obtained from those devices. The capacitance sensor has been developed for determining concentration values. Simulation results from the capacitance sensor indicate that this sensor will work as specified.

It is noted that the sensitivity of the capacitance sensor is relatively low. Therefore it needs to incorporate an active permittivity change detecting device with the sensor. The SAW and capacitance sensors will then operate at the same detection levels.

The performance of a SAW and capacitance sensor incorporated onto one chip for the purpose of determining molecular mass has been characterized. This device performed as expected. Therefore, it is anticipated that equal success will be obtained for a similar sensor device that is used for other applications such as radar, communication systems, and proximity sensing.

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