Dual-Mode Piezo-on-Silicon Resonant Temperature and Humidity Sensor for Portable Air Quality Monitoring Systems

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Abstract—This paper demonstrates a dual-mode, micromachined temperature and relative humidity (RH) sensor platform using two ZnO-on-silicon, lateral-mode bulk acoustic wave (BAW) resonators. A moisture-insensitive reference resonator is utilized in conjunction with an identical, humidity-functionalized resonator to yield a thermally compensated RH sensor. The reference sensor exploits the dual-mode response of fundamental and higher order in-plane resonance modes in the range of 30-100 MHz to eliminate the RH sensor dependence on temperature. Hygroscopic polyethyleneimine (PEI) is deposited on annexed sensing platforms of the BAW resonator to enable operation from 20 to 92 %RH with high Q in air. A humidity sensitivity of 1.2 kHz/%RH from 20 to 60 %RH and 14 kHz/%RH from 60 to 92 %RH is measured at room temperature for the RH sensor which, combined with the reference sensor, occupies a total area of .053 mm².

I. INTRODUCTION
Humidity measurement is essential to various applications such as meteorology, environmental monitoring, smart buildings, and industrial process control. The trend towards system miniaturization has led to the development of resistive, capacitive, and resonant microdevices for humidity measurement and monitoring [1, 2]. Contrary to resistive or capacitive sensors, resonant systems provide information based on frequency which can be digitally measured with high accuracy [3]. Various transduction techniques have been used to implement such devices [4, 5]. Piezoelectric actuation, in particular, has several advantages including low motional impedance, robustness, and operation without DC polarization voltages. Thus, piezo devices promote ease of interfacing with electronics and low-power operation compared to capacitively- [6] or thermally-actuated resonators.

A. Relative Humidity Dependence on Temperature
While absolute humidity refers to the amount of water vapor in a volume of air, it is more useful to consider relative humidity (RH), defined as the ratio of actual water vapor pressure (p_{H_2O}) to the saturation vapor pressure (p^*_{H_2O}) [7]. Because both of these quantities depend on temperature, a humidity sensor requires a compensation mechanism to remove error caused by changing temperature. In addition, a resonant humidity sensor output requires compensation to account for frequency changes due to temperature-dependent material properties. Various passive techniques have been implemented to reduce intrinsic temperature coefficient of frequency (TCF) in silicon resonant devices such as incorporating oxide into the piezoelectric stack [8] and more recently, filling the resonator with oxide pillars [9] or introducing charge carrier depletion [10]. However, it is difficult to achieve a zero TCF at the wafer-level because material compensation techniques are still subject to fabrication process variations [11].

B. Self-Temperature Sensing
The total frequency change of a resonant sensor can be modeled by the sum of frequency changes due to temperature and mass with negligible contributions from other physical parameters [3]. Since it is difficult to obtain individualized temperature and humidity information from a resonant sensor, an external thermometer is often used to provide a local temperature measurement. Humidity sensors with integrated temperature detectors or dual-oscillator systems have been developed to address this challenge [5, 12] but still suffer from large device size to improve humidity sensitivity.

In this work, a humidity sensor with a self-sensing temperature mechanism is implemented. The TCF between two simultaneously excited resonance modes is used to determine the reference resonator die temperature, while an identical BAW resonator with polyethyleneimine (PEI)-coated annexed platforms measures humidity. Any temperature-induced frequency shift in the RH sensor is compensated locally by the reference sensor to determine the correct value.
of RH. These devices form a micromachined resonant temperature and humidity sensor platform. The resonator design with annexed platforms enhances humidity sensitivity without significantly degrading the original resonance mode shape, enabling operation up to the testable limit of 92% RH.

II. SENSOR DESIGN AND FABRICATION

A. ZnO-on-Silicon Lateral BAW Resonators

The sensors are lateral ZnO-on-silicon BAW microresonators (Fig. 1). The resonance frequency in lateral-mode devices is defined lithographically by the length $L$ of the silicon structure. Different frequencies can be defined on the same wafer, enabling sensor array implementation to cover multiple levels of sensitivity. Because mass-loading due to reactions with the target may lead to non-uniform changes in stiffness along the resonator body [8], the sensing material is deposited on platforms separated from the main resonator body by thin supports. The electrodes are designed such that the fundamental and third harmonic lateral modes can be simultaneously excited [13].

B. Humidity Sensor Functionalization

PEI is chosen as the humidity-sensitive polymer for its hygroscopic (water-absorbing) properties [4]. Sensing platforms on the fabricated ZnO-on-silicon resonator [14] are patterned with PEI using the Bioforce Nano eNabler™, a microfluidic cantilever arraying tool capable of depositing nanoliter volumes of solution (Fig. 2). A 1:10 mixture of PEI:alkaline buffer (Bioforce Nanosciences, Inc.) is loaded onto the surface patterning tool (SPT) and deposited onto each platform. The Nano eNabler™ is programmable for wafer-level array patterning of functional materials.

C. Fabrication Process Flow

An SEM image of the released resonator without PEI patterning is shown in Fig. 3. The resonators are fabricated using low-temperature, post-CMOS compatible processes on a 5-µm thick, high-resistivity silicon-on-insulator (SOI) wafer (Fig. 4). First, 0.1 µm of gold is evaporated and patterned by liftoff to create the bottom electrode (Fig. 4a). 0.7 µm ZnO is deposited by RF sputtering with RF power of 125W and heater temperature of 210°C for 100 minutes. The $c$-axis orientation of ZnO, necessary for piezoelectric coupling, is verified through x-ray diffraction, where rocking curve analysis reveals a full-width-half-maximum (FWHM) value of 2.2°. The ZnO film is then patterned in 1:150 acetic acid:DI water to remove ZnO from all areas of the wafer except the active resonator body (Fig. 4b). 0.1 µm of gold is then evaporated and patterned by liftoff to create the top electrode (Fig. 4c). To define the resonator shape, trenches are formed by etching the device layer in an STS ICP system (Fig. 4d). After releasing the device (Fig. 4e), PEI is selectively patterned on the annexed platforms (Fig. 4f).

III. EXPERIMENTAL RESULTS

A. Resonator Response

The resonator frequency response is characterized using an Agilent E8364B Vector Network Analyzer. The reference sensor fundamental resonance frequency $f_1$ and third-order harmonic mode $f_3$ (35 and 86 MHz, respectively) have a measured Q of 1,300 and 2,000 in air, and the RH sensor $f_1$ has Q of 1,340 in air after PEI patterning (Fig. 5).
Fig. 4. Fabrication process flow for ZnO-on-silicon resonators.

Fig. 5. Fundamental peak of RH sensor; \( f_1 = 37 \text{ MHz}, Q = 1340 \) in air.

B. Temperature and Humidity Cycling

All temperature and humidity tests are conducted in a Tenney BTRC environmental chamber. To characterize the reference sensor, the chamber temperature is varied from 25 to 85\(^\circ\)C in 15\(^\circ\)C intervals at constant RH. To characterize the humidity sensor, RH is ramped in 20 %RH intervals from 20 to 92 %RH at constant temperature. Network analyzer measurements of each sensor \( f_i \) and \( f_j \) are recorded after one hour of stabilization.

The RH sensor \( f_i \) response is shown after a rapid RH increase from 20 to 40 %RH at 25\(^\circ\)C (room temperature) (Fig. 6). The sensor frequency tracks very closely with RH and has a response time of less than 25 seconds, limited by measurement setup and network analyzer sweep time.

C. Thermal Compensation of Relative Humidity

Equation (1) models the total change in frequency of the RH sensor as a function of temperature \( T \) and \( RH \). Because both temperature and RH sensors are identical (except for PEI on the RH sensor which minimally affects the mode shape), they are assumed to have the same temperature response. Thus, the temperature-induced frequency change \( \Delta f_{ref}(T) \) is used in place of \( \Delta f_{RH}(T) \). \( \Delta f_{ref}(T) \) and the total \( \Delta f_{RH} \) are measured experimentally to thermally compensate the RH response \( \Delta f_{RH}(RH) \).

\[
\Delta f_{RH} = \Delta f_{ref}(T) + \Delta f_{RH}(RH) \tag{1}
\]

The reference sensor response over temperature \( T \left( ^\circ\text{C} \right) \) at constant RH is shown in Fig. 7. \( \Delta f_{ref}(T) \) is characterized by a combination of \( f_i \) and \( f_j \) denoted as beat frequency \( f_b = 3*f_i - f_j \). Equation (2), extracted from Fig. 7, is used to determine \( TCF_b \). \( TCF_b \) is greater than \( TCF_i \) and linear, making temperature measurement more accurate and future calibration more convenient. Moreover, \( f_{b,ref} \) shows negligible sensitivity to humidity compared to \( f_{b,RH} \) (Fig. 8).

\[
f_{b,ref}(T) = -8.8 \times 10^{-4}T + 19.3[MHz] \tag{2}
\]

The overall humidity sensitivity \( S_{b,RH} \) or \( \Delta f_b/\Delta RH \), determined through measurements over humidity at constant temperature, is plotted against temperature for both sensors in Fig. 8.

In Fig. 9, the uncompensated \( f_i \) response to RH exhibits distinguishable shifts with temperature. To obtain the compensated RH sensor response (Fig. 10), the \( f_i \) vs. RH characteristics at various temperatures are plotted using thermally-corrected \( f_i \) values, confirming that the reference sensor minimizes temperature-induced changes in \( f_i \). The sensor has a measured average hysteresis of 1.8 %RH at 55\(^\circ\)C, the mid-point of the tested temperature range.

Fig. 6. Sensor response for humidity increase from 20 to 40 %RH at 25\(^\circ\)C.

Fig. 7. Sensor response time for RH sensor; \( f_1 = 37 \text{ MHz}, Q = 1340 \) in air.
A third resonator with identical dimensions to the temperature and RH sensors (but no annexed platforms) is patterned with PEI on the active device area to investigate the effect of annexed platforms on humidity sensitivity. The RH sensor with annexed platforms exhibits a higher relative change in frequency $f_i$ than the RH sensor with no platforms (Fig. 11). For values of 40 %RH and above, the annexed platform design responds with greater than four times the relative frequency change compared to the design without platforms (Table I).

### TABLE I. COMPARISON BETWEEN RH SENSING WITH ANNEXED PLATFORMS AND NO PLATFORMS

<table>
<thead>
<tr>
<th>RH (%)</th>
<th>AP $df_i/f_i$ (ppm)</th>
<th>NP $df_i/f_i$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>280</td>
<td>67</td>
</tr>
<tr>
<td>60</td>
<td>835</td>
<td>179</td>
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<tr>
<td>80</td>
<td>2388</td>
<td>349</td>
</tr>
<tr>
<td>92</td>
<td>5126</td>
<td>1014</td>
</tr>
</tbody>
</table>

*Relative change in frequency with respect to conditions at 20 %RH.

### IV. DISCUSSION AND CONCLUSION

This work demonstrates the highest Q micro-resonator used for humidity sensing [15-17] other than the commercially-obtained SAW sensor in [12]. The selectively-patterned sensor has been thermally compensated from 20 to 92 %RH. The PEI layer responds to humidity over the complete compensated range, but the RH sensor has a higher sensitivity of 14 kHz/%RH from 60 to 92 %RH. The annexed platform design shows an increased RH response over a resonator without platforms from 40 to 92 %RH. The RH sensor sensitivity at room temperature is on the same order of magnitude as previous works [12, 15, 17] and the total area of...
combined temperature and humidity sensors is still smaller than other micromachined resonant solutions without a temperature sensor [15].

In summary, a method for temperature and humidity sensing with silicon-based resonant sensors has been presented. When two modes of an uncoated reference resonator with minimal response to moisture are used to monitor the temperature, relative humidity measurements can properly account for changes in ambient temperature. The effects of moisture and temperature on chemical reactions also make temperature and humidity sensing essential to the measurement of gaseous compounds, extending this approach to multiple gas detection in portable air quality monitoring systems. Dual-mode oscillator arrays based on this compensation principle can lead to enhanced sensitivity and selectivity of various environmental contaminants.

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REFERENCES