A novel film bulk acoustic resonator (FBAR) with two resonant frequencies which have opposite reactions to temperature changes has been designed. The two resonant modes respond differently to changes in temperature and pressure, being the frequency shift linearly correlated to temperature and pressure changes. By utilizing the FBAR’s sealed back trench as a cavity, an on-chip single FBAR sensor suitable for measuring pressure and temperature simultaneously is proposed and demonstrated. The experimental results show the pressure coefficient of frequency for the lower frequency peak of the FBAR sensors is approximately -17.4 ppm·kPa⁻¹, while that for the second peak is approximately -6.1 ppm·kPa⁻¹, both of them being much more sensitive than other existing pressure sensors. This dual mode on-chip pressure sensor is simple in structure and operation, can be fabricated at very low cost, and yet requires no specific package, therefore has great potential for applications.

Keywords – FBAR, sealed cavity, pressure sensor, temperature sensor
1. Introduction

Owing to their excellent characteristics and properties, film bulk acoustic wave resonators (FBARs) have been widely used in electronics and communications as oscillators, filters, and duplexers [1, 2]; as well as sensors for sensing physical parameters such as temperature, pressure, humidity and ultraviolet light [3-6], and for detection of various biochemical substances [7-10]. As a sensor, the FBARs have extremely high sensitivity due to their high resonant frequency and small base mass. The performance of FBARs has been further enhanced recently by using a carbon nanotube layer as the top electrode of the devices, and demonstrated quality factors greater than 2000 and mass detection limitation down to \( \sim 10^{15} \text{g} \) [10,11], close to that of a single molecule.

FBARs have two basic structures: the membrane type and Bragg mirror type [8,12,13]. Among the membrane type, there are back-trench membrane type and air-gap type of FBARs. They typically comprise a thin active piezoelectric layer of 1-2 \( \mu \text{m} \) thickness and a supporting membrane of similar thickness. This type of structures has a thin film structure, hence should be very sensitive to pressures or stresses imposed on the membrane, thus FBARs can be used as pressure or force sensors. However, the development of FBAR pressure sensors is very limited though Chiu et al. has successfully demonstrated a back-trench type FBAR pressure sensor with a sensitivity of \(-3.36 \text{ ppm·kPa}^{-1}\) [14]. However, that type of the FBAR pressure sensors is difficult to make as the FBARs were mounted on the head of a dual in-line package, requiring a delicate processing for aligning such small devices. Furthermore for accurate measurement of pressures in application, a temperature sensor and a readout circuitry are always required for calibration, making pressure sensing complicated. Furthermore, the cost and the dimensions of the sensor chips increase significantly. In this work, a simple temperature self-referenced dual-mode on-chip FBAR pressure sensor is proposed.

2. Experimental

The FBARs were fabricated on 4-inch (100)-oriented Si substrates with a thickness of \( \sim 500 \mu \text{m} \). The active area consists of a 2 \( \mu \text{m} \) ZnO piezoelectric layer deposited onto a 2
µm SiO₂ supporting membrane. ZnO thin films were deposited at room temperature using an innovative high target utilization sputtering (HiTUS) system [15-17]. A metallic zinc target of 99.999% purity in a mixture gas of argon and oxygen (both with 99.9999% purity) was used for the deposition. The resulting ZnO thin films were characterized by scanning electron microscopy (SEM), X-ray diffractometry (XRD), atomic force microscopy (AFM), and the stress of the films was estimated using the Stoney equation through measured substrate curvatures before and after film deposition [18].

Figure 1(a) shows an SEM image of the ZnO layer cross-section and the corresponding XRD rocking curve. The SEM picture clearly shows that the ZnO layer consists of columnar structure with (0002) crystal orientation. The full width half maximum (FWHM) of the rocking curve of the (0002) peak is very narrow, about 3.8° as shown in figure 1(b), indicating the small angular dispersion of the crystallites around the c-axis. The films have grain sizes around 50 nm calculated from the XRD measurements [18], much larger than those obtained by standard RF magnetron sputtering, hence guarantees the good piezoelectric properties required for the FBAR device operation.

Figure 2 shows the measured stress as a function of film thickness for the ZnO films deposited by normal RF magnetron sputtering and by HiTUS. The stress for the HiTUS films is lower than 100 MPa for the range of thicknesses investigated, about one order of magnitude smaller than those deposited by RF magnetron sputtering. The room temperature deposition and low defect density generated by ion bombardment in the
HiTUS system is believed to be responsible for the low stress films obtained [18]. Since the as-deposited stress is very small, no annealing was conducted to remove the stress before device fabrication.

Figure 2. Comparison of stress for the films deposited by RF magnetron sputtering and HiTUS process as a function of ZnO thickness. The stress on HiTUS deposited ZnO films is approximately one order of magnitude smaller than those deposited by magnetron sputtering.

The FBARs were fabricated using a four mask process: bottom electrode, via through the ZnO active layer, top electrode and back trench etching. A thin Al$_2$O$_3$ layer of 100 nm was firstly deposited on the back of the Si-wafer by sputtering to define the shape of the membranes. This layer acts as a hard mask for the later etching of Si to form the back trench. The bottom electrodes, consisting of 10/70 nm Cr/Au layer, were patterned using a standard photolithography process and thermally evaporated on the SiO$_2$ layer before sputtering the ZnO active layer. The top electrodes consist of the same metals and thicknesses than the bottom electrodes, and were equally defined by photolithography. A via through the ZnO to the bottom electrode was achieved by selectively wet-etching the ZnO layer in a 2% acetic acid and phosphoric acid solution. Finally the Si from the back of the wafer was removed using a deep reactive ion etch (DRIE) process to release the SiO$_2$/ZnO membrane of 200 × 200 µm dimensions. The detailed fabrication process and ZnO material properties can be found in refs.10 and 11.

The proposed on-chip FBAR pressure sensor utilizes the sealed back trench as the cavity for pressure measurement. Figure 3 shows the schematic structures for a standard FBAR
and the on-chip FBAR pressure sensor with the back trench sealed. Once sealed, the pressure inside is constant if the temperature is fixed, so that any pressure variation outside of the cavity will induce a pressure difference across the membrane which is to be measured. For applications, the detection system with the pressure sensor needs to be inserted a system with pressure to be measured. For measuring the pressure response in this experiment, the FBARs were bonded on a Si wafer using photoresist AZ5014 to seal the back trench as shown in figure 3(b). The photoresist was spin coated at 300 rpm for 10 s to obtain a thickness about 10 µm (measured by a KEYENCE VK-9710 profilometer). The photoresist was prebaked at 100 °C for 60 s to vaporize the solvents, and the FBAR chips were placed on the photoresist with the assistance of a soft touch to ensure the FBARs are bonded without any leakage.

![Figure 3. Schematic view of the back-trench FBAR device (a) and the proposed FBAR with sealed cavity for pressure sensing (b). The cavity size is 200 x 200 x500 µm³.](image)

The transmission and reflection characteristics of the FBAR devices were measured using a probe station with a GSG coplanar probe connected to an Agilent E5071C network analyzer. The temperature dependence of the transmission characteristics of FBARs with and without the cavity sealed was investigated in the temperature range from 25 to 135 °C using a temperature controller, as displayed by figure 4(a), with a resolution of ±0.2 °C.

3. Results and discussions

The typical transmission and reflection characteristics of the fabricated FBAR devices are
shown in figure 4(b), where two distinctive resonant modes can be seen at $f_1 \sim 786$ MHz and $f_2 \sim 1.56$ GHz. The higher frequency mode corresponds to the resonance of the ZnO layer, while the lower frequency one corresponds to the resonance of the combined ZnO and SiO$_2$ membrane [10]. The effective coupling coefficient, $K^2_{\text{eff}}$, can be approximated by equation (1) [19],

$$K^2_{\text{eff}} = \frac{f_p^2 - f_s^2}{f_p^2}$$

where $f_p$ and $f_s$ are the parallel and series resonant frequencies. $K^2_{\text{eff}}$ was found to be 1.2% and 4.7% for the first and the second mode resonances respectively. The quality factors, $Q$, were calculated using the 3-dB method [20], and were found to be 1310 and 260 respectively for the first and second modes of this device.

Figure 4 shows the frequency shift of both modes with temperature. The first resonance mode exhibits a positive linear frequency shift with temperature rise in both the sealed and unsealed devices; but the gradient for the sealed FBARs is smaller than that of the unsealed ones. However, the second resonance mode, exhibits a negative linear frequency shift with temperature rise in both types of the devices, and the gradient for the sealed FBAR is greater than that of the unsealed one.

The temperature coefficient of frequency (TCF) of a resonator is defined as:
\[
TCF = \frac{1}{f_0} \frac{\Delta f}{\Delta T} \times 10^6 [\text{ppm/K}]
\]  

From figure 5(a), \( \Delta f/\Delta T = 0.05458 \) is obtained for the unsealed first mode. For simplicity, the measured original resonant frequency, 786 MHz, of the FBAR at \( T_0 = 25 \, ^\circ \text{C} \) was used as \( f_0 \). The TCF of the first mode resonance is then found to be 69.5 ppm/K for the unsealed FBAR, and the second mode resonance has a smaller TCF of -8.1 ppm/K. The thermal expansion coefficients of SiO\(_2\) and ZnO materials are 0.5 ppm·K\(^{-1}\) [21] and 2.5~5 ppm·K\(^{-1}\) [22] respectively, depending on the deposition technologies. Also the propagation velocity of acoustic waves in most materials changes with temperature due to variations on their elastic matrix. For a temperature rise, the longitudinal velocity in SiO\(_2\) increases (~ppm·K\(^{-1}\) [23]), while it decreases in ZnO (~-12 ppm·K\(^{-1}\) [22, 24]). The combined effect of thermal expansion and velocity change with temperature results in different TCFs for these resonant modes. For the first mode, the TCF is the combined result of ZnO and SiO\(_2\) layers. For the unsealed devices, an experimental TCF of 69.5 ppm·K\(^{-1}\) was measured, in agreement with the theoretical TCF (~72 ppm·K\(^{-1}\)). For the sealed devices, an experimental TCF of 63.3 ppm·K\(^{-1}\) was measured, approximately 9% lower than the sealed devices. Similarly the TCFs for the second resonant mode can be obtained. For the unsealed devices, an experimental TCF of -8.1 ppm·K\(^{-1}\) was measured, and -10.2 ppm·K\(^{-1}\) for sealed devices, an increase of 26%. The response to temperature change for the two modes is opposite, but the low frequency peak has a higher sensitivity to temperature change, and it is better for temperature sensing. As both the resonant modes have excellent linearity, FBARs can be good temperature sensors, and has been intensively studied for the applications, especially for wireless sensing [25,26].
Figure 5. Resonant frequency shift as a function of temperature for FBARs with and without sealed back trench, showing different temperature coefficients. This is caused by the pressure increase in the sealed cavity (a) mode I and (b) mode II.

Once the back trench is sealed, the pressure inside the cavity is isolated from the outside; hence the FBAR can be a good pressure sensor despite the volume of the cavity being very small. Hereafter it will be demonstrated that one single FBAR can be an excellent pressure sensor with very high sensitivity, and it can be used to measure the pressure and temperature simultaneously.

The membrane bending under a pressure may introduce a volume change for a sealed FBAR device, but for pressures less than 1 MPa as will be shown later, the bending in the middle of the membrane was found to be much smaller than 1 µm calculated using equations in ref.27. The deflection of the membrane was also measured by confocal optical microscope, and confirmed to be much lower than 100 nm at 100 °C. Therefore, the volume change of the cavity during temperature (pressure) change is less than $10^{-4}$ which can be ignored compared to the whole cavity’s volume. Therefore the pressure sensitivity of the FBARs can be estimated using the results shown in figure 5. As temperature increases, the pressure difference inside and outside of the cavity rises, which results in a frequency shift for both the resonant modes. Assuming that the volume of the cavity does not change with pressure as discussed above, then the relationship between pressure and temperature of the sealed cavity is governed by [28],

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

(3)

where the index 1 and 2 are the initial and final temperatures and pressures of the device respectively; and the unit of temperature is Kelvin. When the temperature changes, the
pressure inside the cavity changes correspondingly as follows,

\[ \Delta P = \Delta T \cdot \frac{P_1}{T_1} \]  

(4)

To a first order, the frequency shift of piezoelectric devices induced by temperature variation is a linear relationship as shown by many piezoelectric devices [29] and by FBARs [14]. Therefore the difference in frequencies for the sealed and unsealed FBARs shown in figure 5 is induced by the pressure increase due to the expansion of the air sealed in the cavity with temperature rise. Figure 6 shows the frequency shift as a function of pressure for both resonant peaks as calculated from figure 5 and equation (4). The experimental data shown in figure 5, instead of the fitted lines, were used for the pressure calculation for figure 6 to maintain the originality of the data; this led to larger scatter of the data points round the linear fitted lines than those shown in figure 5.

The pressure coefficient of frequency (PCF) of a FBAR is defined as:

\[ PCF = \frac{1}{f_0} \frac{\Delta f}{\Delta P} \times 10^6 \text{[ppm/kPa]} \]  

(5)

From figure 6 and equation (5), the PCFs were found to be -17.4 ppm·kPa⁻¹ and -6.1 ppm·KPa⁻¹ for the first and the second mode resonances of the ZnO FBARs, respectively. For the first mode, the PCF is about five times higher than that obtained by Chiu et al [14], and an order of magnitude higher than that (-1.33 ppm·kPa⁻¹) of the ZnO/Quartz surface acoustic wave-based pressure sensor [29]. Even the second mode is higher than the pressure sensors reported by others, showing that the on-chip FBAR devices can be pressure sensors with very high sensitivity, though the pressure range is yet to be fully investigated. The higher sensitivity of our devices compared to that obtained by Chiu et al is believed to be caused by the different thickness of the piezoelectric layer and device dimensions which were not given in ref.14. The resolution for the network analyzer is typically very, able to measure the transmission signal down to level of -80dB. The main problem for any measurement using resonant frequency is the difficulty to precisely determine the resonant peak position which always jumps around the resonance. For the network analyzer used for the experiments, the minimum frequency resolution can be determined with reasonable accuracy is in the range of <2kHz [9,10], therefore the detection limitation can be calculated to be 140 and 400 Pa for the first and the second mode resonances of the FBARs, respectively. This can be further improved if the measurement is taken place with zooming-in at the frequency range round the peak and
using a smooth function to extract the peak frequency.

![Graph of frequency shift vs. pressure change for a FBAR device, showing a good linearity. (a) is for mode I and (b) for mode II.](image)

Figure 6. Frequency shift as a function of pressure change for a FBAR device, showing a good linearity. (a) is for mode I and (b) for mode II.

The response of the FBAR to pressure was not investigated at this stage, but the response to temperature variation is instantaneous. The response time is expected to be much less than microseconds owing to the fast response of the piezoelectric effect, but is yet to be confirmed.

The above experimental results and analysis clearly show that a pair of FBAR devices with the back trench sealed and unsealed can be simply used for direct temperature and pressure sensing. The temperature can be measured by the unsealed FBAR, whereas the dual-mode resonances can increase the accuracy and sensitivity to the temperature. The temperature can then be used as the temperature reference for the sealed FBAR to measure the pressure imposed. On the other hand, the responses to the temperature and pressure by the two resonant peaks are different; hence it is also possible to sense the temperature and pressure simultaneously by a single FBAR device. The frequency shifts, $\Delta f$, induced by temperature and pressure changes for the two resonant peaks of one device can be expressed as follow;

$$\Delta f_1 = \alpha_1 \Delta T + \beta_1 \Delta P$$

$$\Delta f_2 = \alpha_2 \Delta T + \beta_2 \Delta P$$

Here $\alpha = \text{TCF, } \beta = \text{PCF, } \Delta f, \Delta T$ and $\Delta P$ are the changes of resonant frequency, temperature and pressure, and the index 1 and 2 represent the initial and final states of the device. Rearranging the equations, we can obtain the following equations for $\Delta T$ and $\Delta P$, 

$$\Delta f_1 = 0.06496 - 0.01369 \Delta P$$

$$\Delta f_2 = 0.00394 - 0.00958 \Delta P$$
\[ \Delta T = \frac{\Delta f_2 - \beta_2 \Delta f_1}{\beta_1 \beta_1} \]  

(8)

\[ \Delta P = \frac{\Delta f_2 - \alpha_2 \Delta f_1}{\alpha_1 \alpha_1} \]  

(9)

Equations (8) and (9) can be used to sense the changes of temperature and pressure simultaneously using a single FBAR device measurement. The principle of a single FBAR for sensing two parameters simultaneously can also be applied to other parameters such as the combination of temperature and humidity, or temperature and biomarkers etc as demonstrated by our previous work [10], clearly demonstrating the superiority of the FBAR sensors with dual resonant frequencies for sensing applications. However it also indicates that an attention should be paid to packaging of FBAR devices for various applications to avoid errors possibly induced by pressure related frequency shift.

4. Conclusion

In summary, this work proposed a single on-chip FBAR pressure and temperature sensor and demonstrated the working principle by utilizing the sealed back trench as the cavity isolated from the outside. FBARs exhibited a good linearity of frequency shift with temperature and pressure with PCFs of -17.4 ppm·kPa\(^{-1}\) and -6.1 ppm·kPa\(^{-1}\) for the two resonant peaks. By using these dual mode FBARs, it is possible to sense temperature and pressure simultaneously. This dual mode on-chip pressure sensor is simple in structure and operation, can be fabricated at very low cost, and yet requires no specific package, therefore has great potential for applications.

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