PRECISION HIGH-BANDWIDTH OUT-OF-PLANE ACCELEROMETER AS CONTACT MICROPHONE FOR BODY-WORN AUSCULTATION DEVICES

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ABSTRACT

This paper reports on the implementation and characterization of wafer-level-packaged accelerometer contact microphones having wide bandwidth (f_{res} >10 kHz) and low-noise (<100 µg√Hz) for use as auscultation devices in body-worn sensor arrays. By using wide bandwidth capacitive accelerometers as contact microphones, the encapsulated sensor can detect not only internal sounds from organs but also body motions down to DC frequency levels, significantly reducing sensor size and fabrication cost of wearable technology for health monitoring. The out-of-plane micro-g accelerometers use nano-gap transducers (270 nm) for enhanced signal-to-noise ratio in a high resonant frequency microstructure with small form-factor. Fabricated devices were interfaced with off-the-shelf readout circuits and their performance was compared to commercially available piezoelectric contact microphones. Normal breath sounds in the range of 600-1000Hz along with phonocardiogram (PCG) and ballistocardiogram (BCG) signals are extracted by mounting the device on the chest.

INTRODUCTION

Cardiovascular and cardiopulmonary diseases are considered the leading cause of mortality globally. The interdependency of cardiac and pulmonary health [1] makes continuous monitoring of cardiopulmonary parameters essential for an accurate and timely diagnosis. The use of an auscultation device such as a stethoscope is considered as the first step in clinical evaluation of cardiovascular conditions and a very powerful tool available to physicians.

There is a growing demand for high performance electronic auscultation devices due to their ability to augment traditional clinical equipment for instance, by allowing the physicians to remotely diagnose and track patient health post-treatment. Capturing body motion coupled with the auscultation data can allow physicians to correlate cardiopulmonary sounds to daily activities. Additionally, monitoring the timing of abnormal breath sounds with respect to respiratory cycle is of great interest to doctors for accurate diagnosis [2].

Typical electronic stethoscopes use membrane-type microphones which operate by generating an electrical response to pressure changes in air caused by sound waves. This technique is susceptible to environmental noise and may suffer due to insufficient acoustic energy transfer. The piezoelectric-type stethoscope produces electrical signals due to distortion of a piezo-crystal coupled to the stethoscope diaphragm. Again, due to distortion, this technique does not accurately capture the sound and resultant output may differ from the original tone [3]. Moreover, performance of such microphones is limited by their size [4], and are unable to capture low frequency signals such as respiratory rate and body motion.

A novel approach to tackle these challenges is a capacitive accelerometer contact microphone. A micro-g accelerometer with large bandwidth (f_{res} >10 kHz) and low noise (<100 µg√Hz) out-of-plane sensitivity is essentially a contact microphone. By having a high resonant frequency, the accelerometer can pick up µg-level accelerations produced by acoustically vibrating structures. Such a microphone is not sensitive to air-borne acoustic emissions; only sensitive to vibrations from its contact surface. Its small size allows it to replace bulky stethoscopes with ergonomic wearable auscultation systems that can precisely measure cardiopulmonary sounds, chest wall motion, ballistocardiogram (BCG) signal as well as body motion of the user simultaneously. This opens new gateways in telemedicine and remote health monitoring. Moreover, such an integrated solution significantly reduces fabrication cost of wearable technology, making it more accessible and affordable to the masses.

In this paper, a low noise, wide bandwidth out-of-plane accelerometer with nano-gaps (270nm) capacitive electrodes implemented using HARPSS+ process [5] is fabricated and characterized as a contact microphone. The performance of the accelerometer contact microphone (ACM) is compared with a commercial piezoelectric contact microphone. Further, the paper addresses the use of this contact microphone as a body-worn auscultation device by mounting it on the chest and recording sounds produced in the thoracic cavity. The recorded signals are filtered and processed to extract the heart sound and BCG signal from the recorded data. Similarly, lung sound and chest wall motion are extracted using data processing techniques, demonstrating the possibility of accurately capturing multiple types of acoustic and vibrational data from the body at the same time.

ACCELEROMETER CONTACT MICROPHONE

It is useful to express vibration in terms of acceleration, rather than velocity or displacement, due to availability of a wide range of low-cost accelerometers. To capture high quality audio signal using an accelerometer as a contact microphone, small MEMS accelerometers with wide operational bandwidth and micro-g resolution are needed.

Considering use of an encapsulated accelerometer as a contact microphone, there is an absence of a through-hole to generate any acoustic pressure on the MEMS device. The acoustic vibrations are therefore expressed in units as 'Vibration Acceleration Level (VAL)' rather than 'Sound Pressure Level (SPL)', which is given by equation (1), where a_{ref} corresponds to a reference acceleration, typically 1 µg (9.8 µm/sec^2) [6].

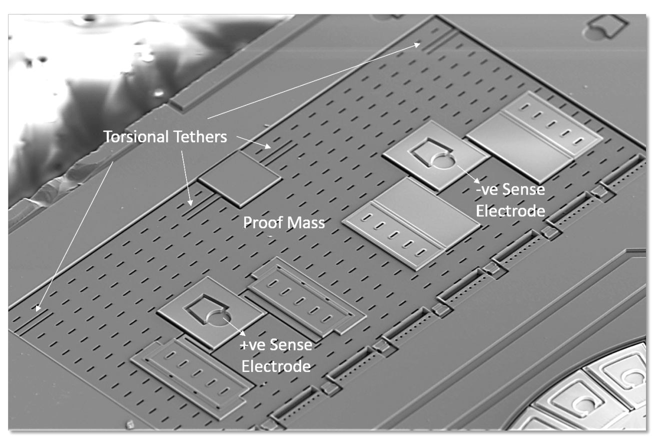

Figure 1: SEM view of the accelerometer contact microphone

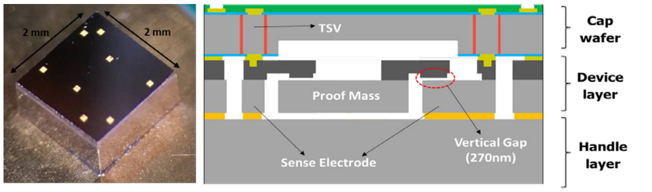

Figure 2: The wafer-level-packaged ACM die (left) and its cross-sectional schematic showing differential capacitive sensing scheme.

$$L_a = 10\log\left[\left(\frac{a}{a_{ref}}\right)^2\right] \quad dB \tag{1}$$

The sensitivity of a microphone is defined as the ratio of the electrical output of the device to a given standard acoustic input. Typical acoustic microphones use a 1 kHz sinusoidal signal at 94 dB SPL (equivalent to 1 Pa pressure) as the standard pressure input [7] for characterization. Analogous to pressure input, the sensitivity of the contact microphone can be characterized by measuring the electrical response to a standard vibration input of a 1 kHz sinusoidal signal at 120 dB VAL (equivalent to 1 g acceleration).

Design and Fabrication

A torsional cantilever topology [8] is chosen to implement the micro-g accelerometer, wherein the proof mass is supported by torsional tethers at one end. When acceleration is applied in out-of-plane direction, generated torque will rotate the proof-mass, changing the capacitance between sense electrode. To maintain a small form factor, the sense electrodes are placed within the proof mass, and a differential top electrode configuration is employed to suppress common mode noises. The device is fabricated using the HARPSS+ process on an SOI (Silicon-on-Insulator) wafer having 40µm thick device layer with ~270nm capacitive gaps [5, 9] . After the releasing process, completed wafer is then wafer-level packaged using eutectic bonding to a silicon capping wafer with built-in through-silicon-vias (TSV). Fig. 1 shows the SEM of the uncapped ACM device and Fig. 2 shows the wafer level packaged die and the device cross section.

MEASUREMENT RESULTS

Interface Electronics

The microphone is interfaced with MS3110 [10], a commercially available off-the-shelf capacitive readout circuit. A miniature PCB (0.8 inch × 0.8 inch) is designed to accommodate the sensor and interface circuit by utilizing the front and back side of the board to mount the MEMS device and interface IC. The MEMS die is covered using Dow 7920 adhesive to protect the bond wires from accidental damage as shown in Fig. 3.

Device Characterization

To measure sensitivity, the evaluation board is mounted on the shaker table and a sinusoidal 1 g acceleration is applied at 1 kHz frequency. Dynamic Signal Analyzer 35760A is used to precisely measure the scale factor, showing 72.6 mV/g (-22.76 dB relative to 1V/g) as plotted in Fig. 4. The resonant frequency of the device was measured by placing uncapped device into the vacuum chamber and exciting electrostatically using network analyzer E5061B. Fig. 4 shows the measured resonant frequency of 12.5 kHz, confirming high operational bandwidth.

The Allan deviation (ADEV) plot is extracted by sampling the output at 1 kHz using NI 9220 Data Acquisition (DAQ) card. The measured velocity random walk (VRW) and bias instability (BI) are 85µg/√Hz and 82µg, respectively, as shown in Fig. 4. Due to limited capacitive resolution of the interface circuit, the overall noise of the system is dominated by the electronics. By replacing the MS3110 with a dedicated low-noise ASIC, the overall noise can be lowered to the point where it gets dominated by mechanical noise, which is less than < 20 µg/√Hz. Table 1 provides a summary of the characterization results.

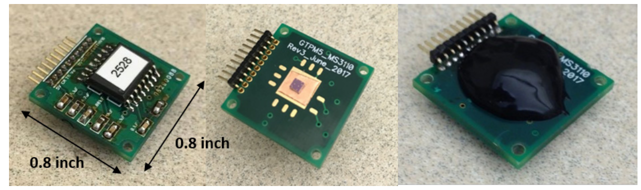

Figure 3: Miniature PCB with MEMS die covered in epoxy.

Table 1 Performance Summary

MEMS Device Only	
Sensor dimension	1.6 mm x 0.8 mm
Nano-gap Size	270 nm
F_{res}	12.5 kHz
MEMS Device + Interface IC	
Scale factor	72.6 mV/g (-22.76 dB rel. 1V/g)
VRW	85µg/√Hz
Bias Drift	82µg

ACOUSTIC CHARACTERIZATION

The performance of the ACM is compared with a commercially-available piezoelectric contact microphone (Knowles BU-23173) [11], which is often used as gold standard in acoustic measurements. The form-factor of the MEMS ACM is ~10x smaller than the Knowles BU-23173 microphone.

Audio Reconstruction Test

An audio reconstruction test is performed to validate the functionality of the ACM by mounting alongside the Knowles BU-23173 microphone on a speaker system. A test audio signal is played over the speaker, and the output from the microphones are recorded using NI-9220 DAQ at 8 kHz sampling frequency. Using a

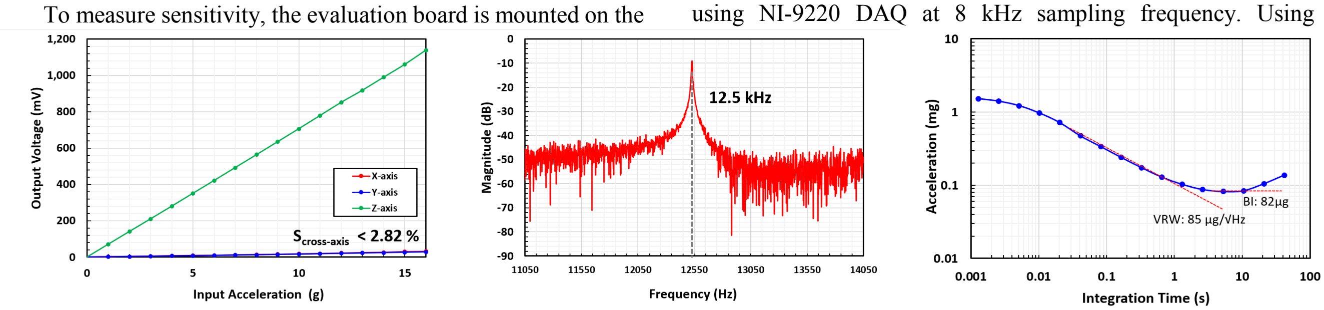

Figure 4: Measured (a) scale-factor, (b) resonant frequency and (c) Allan Deviation for the accelerometer contact microphone

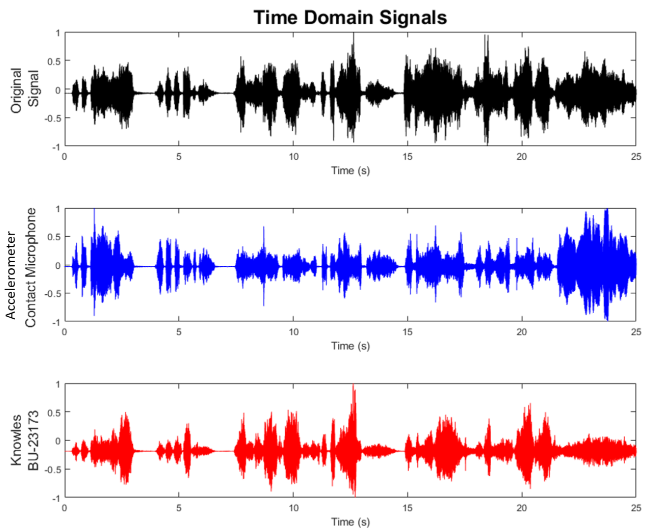

Figure 5: Audio Reconstruction Test showing time domain signals of original and recorded signals

MATLAB program, the captured data is reconstructed into an audio file format for playback. Fig. 5 shows the time domain signals for the original audio clip along with the recorded data. A high degree of similarity is observed between the recorded sounds and original audio clip. High frequency components (>2 kHz) are not picked up by the ACM due to its operation in air. However, on playback, the ACM demonstrates high quality signal specifically at lower frequencies compared to the Knowles microphone which exhibits noticeable distortion. This behavior can be attributed to the ACM's inherent ability to capture high quality signals at low frequencies, including the inaudible range (0-20 Hz), unlike the piezoelectric contact microphones.

BODY-WORN AUSCULTATION DEVICES

Sensor Placement

Several auscultation locations for cardiopulmonary sounds are available in the intercostal spaces (ICS) (i.e. the space between two consecutive ribs) on the chest. Cardiopulmonary sounds, which lie between 20 to 2500 Hz frequency range [12], are recorded by mounting the sensor left of the sternum in the 5th intercostal space, shown in Fig. 6. The PCB is held in place using a chest strap to provide firm contact between the board and skin. Such configuration is essential to pick-up high-fidelity audio signals.

Cardiopulmonary Sound Sensing

The senor board is interfaced with NI-9220 DAQ to collect the data and a MATLAB program is used to filter the recorded signals which can be further stored in audio file format for playback. Unlike piezoelectric microphones, the ACM can measure accelerations

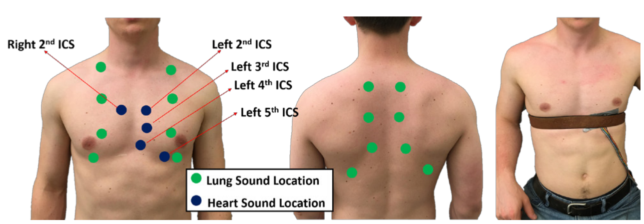

Figure 6: Sensor placement on the body for heart and lung sound acquisition

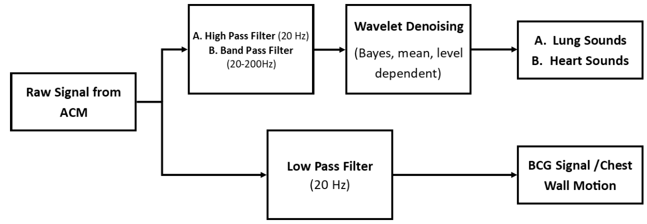

Figure 7: Filtering algorithm for extraction of high frequency sound signal and low frequency motion signal

down to DC level. This attribute is used to obtain additional information such as body motion, heart rate, respiratory rate and even BCG signal. Moreover, using an array of the ACMs can result in high-precision activity detection of the user, thus providing an additional layer of information for correlation of auscultation to daily activities. The higher frequency components (> 20Hz) of the recorded signal correspond to the cardiopulmonary sounds.

The filtering algorithm shown in Fig. 7 is used to separate the low frequency component of chest wall motion and the high frequency component of the sound signal. The filtering is performed using high-order Butterworth filters on the basic criteria of audible (> 20Hz) and inaudible frequencies (< 20Hz). A wavelet denoising technique is used on the high frequency components to reduce noise and extract signal features [13]. The resultant waveforms are shown in Fig. 8, corresponding to extracted cardiopulmonary signals.

There are two major cardiac sounds; S1 and S2, which occur due to closing of the atrioventricular valves (Mitral and Tricuspid) and closing of the semilunar valves (Aortic and Pulmonary), respectively. The period from S1 to S2 is known as Systole, whereas the S2 to S1 period is known as Diastole [14], as shown in Fig. 8. The recorded signal, known as phonocardiogram (PCG), is characterized by a 'lub-dub' sound, and provides a solid foundation for preliminary diagnosis, based on the frequency content and amplitude of the signal, of any cardiac disease.

Another feature captured along with the heart sounds is the ballistocardiogram (BCG) signal, defined as the micro-movements of the body due to shift in center of mass with the pumping of blood at every heartbeat [15]. As this signal lies in the frequency range of 0-20Hz, it is typically captured using a precision micro-g accelerometer. The dual nature of the proposed contact microphone enables the detection of the BCG signal, while measuring cardiac sounds. As shown in Fig. 8, the BCG signal is characterized by the H, I, J, K, L wave, forming a 'W' pattern within the waveform. The importance of capturing this waveform is marked by its unobtrusive nature and ability to detect early onset of several diseases such as acute myocardial disease, asymptotic coronary artery disease and congestive heart failure [16].

Auscultation of the lungs provides vital information regarding their physiology such as obstructions in airway or presence of liquid in the organ. The qualities of breath sounds modify as air passes through the lungs. The pitch and duration of recorded lung sounds differ with respect to location of the senor. The presence of adventitious breath sounds such as crackles or wheezes usually indicate disease [2]. To accurately identify the timing of abnormal breath sounds within a respiratory cycle, the inspiration and expiration can be monitored by tracking the movement of the chest wall. Normal "vesicular" breath sound recorded by our accelerometer contact microphone is shown in Fig. 8.

The ACM demonstrates high-fidelity cardiopulmonary auscultation sensing capability as well as high sensitivity towards motion artifacts. Characteristic features of heart sounds, BCG signal and lung sound are easily detected using the ACM.

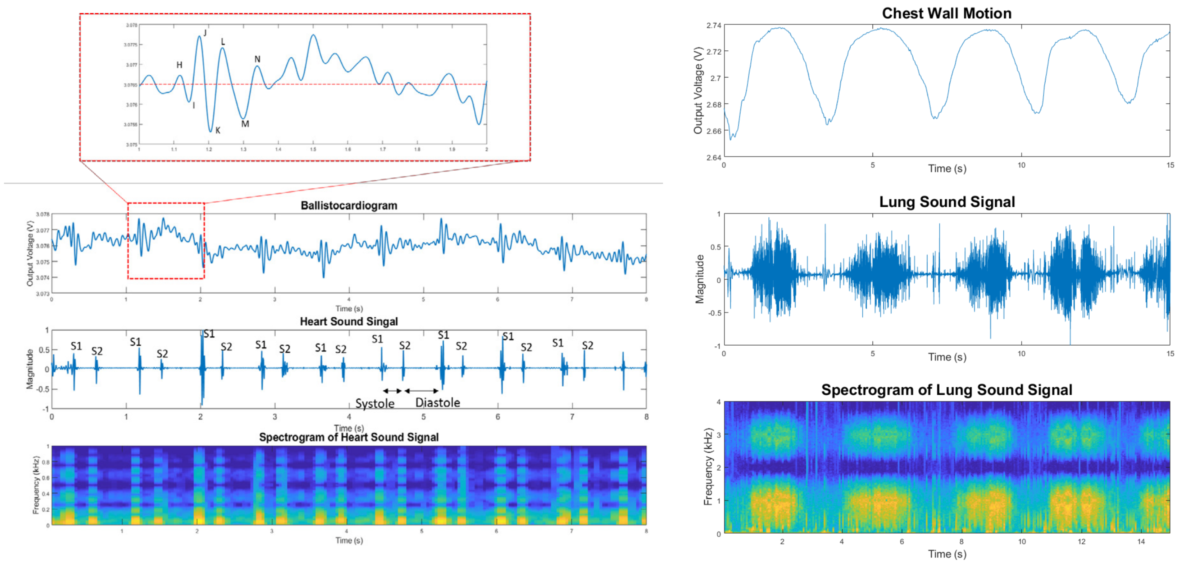

Figure 8: Recorded heart (left) and lung(right) sounds when the subject is sitting idle and breathing heavily respectively. The spectrogram shows the frequency content of the sound signal and its variation with heartbeats and respiratory cycle.

CONCLUSION

The growing demand for remote health monitoring and wearable technologies will necessitate the integration of sensors into smaller form-factor with increased functionality and precision performance. The presented accelerometer contact microphone, whose functionality and feasibility are validated by an audio reconstruction test followed by an on-body auscultation test to capture heart and lung sounds, along with simultaneous recording of BCG signals and chest wall motions, represents as a major step towards this goal. By integrating the functionality of a microphone and an accelerometer in a single MEMS device, the cost of manufacturing wearable devices can be reduced significantly. Using this device, a physician can observe heart and lung sounds remotely with more accuracy and precision than a conventional stethoscope, while having access to low-frequency chest motions and body activities for extracting additional information. Additional degrees of freedom of motion sensing can be added to the same die, e.g. a tri-axial wide-bandwidth micro-g accelerometer can be implemented using the same process platform technology.

ACKNOWLEDGEMENT

This work was supported by a grant from the Georgia Tech Institute for Electronics and Nanotechnology (IEN). The fabrication of the WLP MEMS accelerometers were supported by the DARPA MTO Single-Chip Timing and Inertial Measurement Unit (TIMU) program under contract # N66001-11-C-4176.

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