PIEZOELECTRIC MEMS MICROPHONE NOISE SOURCES

Robert Littrell[1] and Ronald Gagnon[1]*
[1]Vesper, Boston, Massachusetts, USA

ABSTRACT

Piezoelectric MEMS microphones have been researched for more than 30 years. Despite many advantages, they have not seen widespread use because the signal-to-noise ratio (SNR) has been poor relative to capacitive MEMS microphones. This work describes piezoelectric MEMS microphones, utilizing aluminum nitride as a piezoelectric material, with a better SNR than many capacitive MEMS microphones on the market today. Further, this work describes and measures the noise sources in these microphones. Piezoelectric MEMS microphones with an SNR of 66 dB and 68 dB are presented.

INTRODUCTION

MEMS microphones are used in ubiquitous devices such as smart phones, tablets, and laptop computers, as well as emerging markets such as hearables and smart home devices. The microphone market is not only large but also growing rapidly. IHS, a market research firm, predicts that the MEMS microphone market will grow to 5.8 billion units per year by 2019 [1]. Many applications for microphones use arrays of microphones to focus on specific sound sources and filter out background noise. For these applications, microphone signal-to-noise ratio (SNR) and microphone matching are of the utmost importance [2, 3].

Today, all MEMS microphones on the market use capacitive sensing. Capacitive MEMS microphones typically consist of a moving diaphragm and a stationary backplate. As sound pressure causes the diaphragm to move, the distance between the diaphragm and backplate changes, causing a change in capacitance. These MEMS microphones also contain an application specific integrated circuit (ASIC). This ASIC contains circuitry to provide either a bias voltage or bias charge between the diaphragm and backplate. When the voltage or charge is held constant, the change in capacitance causes a change in charge or voltage, respectively. The ASIC then contains additional circuitry to generate an output voltage proportional to this change in charge or voltage. Capacitive MEMS microphones have been commercialized for nearly 15 years [4] and have undergone significant improvements in performance.

While capacitive MEMS microphones today are very small and achieve good performance compared to other commercially available microphones, they also have some negative aspects. Although the SNR of capacitive MEMS microphones reaches 66 dB – 67 dB [5, 6, 7], microphone customers still want better SNR. A significant noise source in capacitive MEMS microphones is the acoustic thermal noise caused by squeeze film damping between the diaphragm and backplate. Another limitation of capacitive MEMS microphones is that they are sensitive to dust and water. If a dust particle gets between the diaphragm and backplate, the microphone performance is reduced [8, 9]. Capacitive MEMS microphones can also shift in performance or fail if the diaphragm sticks to the backplate (called stiction). This can happen if the microphone is exposed to water or other liquids or can be caused by solder/flux as the microphone is installed in a device [10]. The diaphragm can also stick to the backplate if they come in contact due to high sound pressure levels. Sensitivity to dust and water are especially important for array applications because any drift in performance will cause the microphones to become unmatched. Therefore, even if a microphone array is built with well-matched microphones, environmental contaminants can cause the array performance to be lost over time.

Piezoelectric MEMS microphones have been a topic of research since the early 1980s [11]. Piezoelectric MEMS microphones are an attractive alternative to their capacitive counterparts because piezoelectric MEMS microphones do not require the generation of a bias charge or voltage, simplifying the ASIC. Also, these microphones do not have a small capacitive sensing gap. Because piezoelectric MEMS microphones do not have the small sensing gap, one of the main noise sources in capacitive MEMS microphones, squeeze film damping, is not present in piezoelectric MEMS microphones. The absence of a small sensing gap also removes the primary source of performance degradation due to environmental factors such as dust and water. Today, much of the work on piezoelectric MEMS microphones is focused on their use in aeroacoustic applications, where environmental robustness is critical [12].

This work differs from previous works by this author in that this is the first time that an integrated circuit has been used to buffer the signal. Previous works used a discrete JFET in a common source amplifier circuit to buffer the signal [13]. By using an integrated circuit, the circuit noise can be reduced, allowing other noise sources to be measured. This work also demonstrates improved performance compared to that published in previous works.

METHOD

Piezoelectric MEMS microphones contain three parts, the MEMS transducer, the ASIC, and the package. Each of these parts is critical to the overall microphone performance. The design and fabrication of each part and the testing process are summarized in this section.

MEMS Transducer

The MEMS transducers were built at GLOBALFOUNDRIES on 200 mm wafers. An illustration of a cross-section of the MEMS die is shown in Fig. 1. The microphones consist of two layers of aluminum nitride (AlN) interspersed between three metal electrode layers. Because acoustic pressure causes an in-plane stress and the electrodes are oriented on top and bottom of each layer, this device uses the 3-1 mode of operation. During bending, the direction of stress in the top half of the cantilever plate is opposite to that in the bottom half. Therefore, by using two AlN layers and a center electrode, both layers can generate signal and contribute to the microphone output.

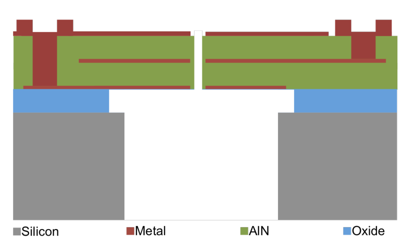

Figure 1: Cross-section of MEMS transducer. The MEMS transducer has two AlN layers interspersed between three metal electrode layers. The structure is isolated from the silicon substrate by a silicon dioxide layer.

A top-down image of the MEMS die is shown in Fig. 2. The MEMS transducer consists of four triangular plates, each fixed to the substrate at the base of the triangle and free at the tip. One key design metric is the gap size between the plates. This gap size, in combination with the package geometry, will determine the low-frequency roll-off characteristics of the microphone. This geometry was selected in order to minimize the change in gap size caused by plate bending due to residual film stress variation. In this design, each plate is 490 µm from the base to the tip. The total die is 1.4 mm X 1.4 mm and it is 400 µm thick. The capacitance of the MEMS die is about 1.5 pF.

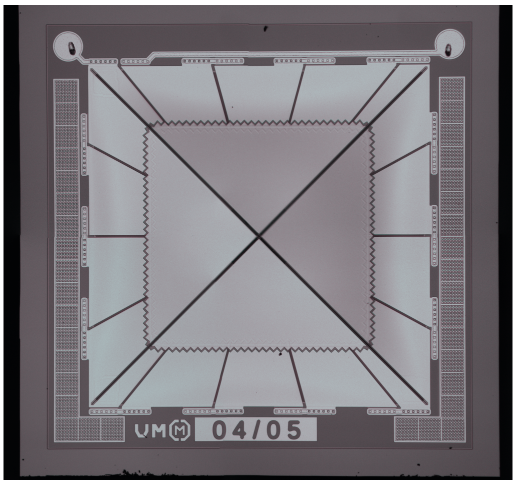

Figure 2: Microscope image of MEMS transducer die. The MEMS transducer consists of four triangular plates, each fixed to the substrate at the base and free to move at the tip.

ASIC

The signal that comes out of the MEMS die is at the mV level but the output impedance is high. Due to this high output impedance, the output is susceptible to electromagnetic interference and cannot drive low impedance loads. Therefore, an ASIC must be placed close to the MEMS die in order to buffer the output signal. This ASIC is built in a 180 nm CMOS process and consists of a single stage to buffer the output signal. The current consumption is 220 µA and it is designed to contribute minimal noise to the overall noise floor of the microphone.

Package

The MEMS die and ASIC are both placed into a microphone package. The packaged microphone is shown in Fig. 3. This package consists of a substrate and a metal lid. The package serves several purposes. First, the MEMS transducer is sealed to the substrate around the microphone port. Therefore the back cavity of the microphone prevents sound pressure from reaching the opposite side of the transducer and cancelling with the pressure on the front of the diaphragm. Additionally, the metal in the package substrate along with that in the lid provides a shield to electromagnetic interference. The total package size for this study is 3.76 mm X 2.95 mm X 1.10 mm. This package size provides for a back cavity volume of approximately 4.6 mm^3. This back cavity volume also adds stiffness to the system, reducing sensitivity. A complete model of the package is necessary to effectively predict microphone performance. Several examples can be found in the literature [12, 13, 14, 15].

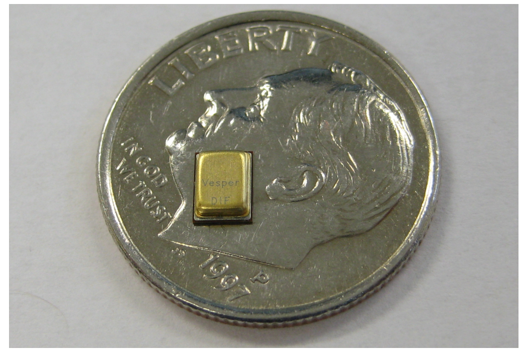

Figure 3: Packaged MEMS microphone on a dime for scale. This package is 3.76 mm X 2.95 mm X 1.10 mm.

Testing

The microphones were tested using a plane wave tube system as described in previous work [16]. In this system, a speaker sends a plane wave down a tube of small diameter. The diameter of the tube ensures that only plane waves can travel through the tube at frequencies below about 30 kHz, with higher order modes being evanescent. Several cm from the sound source is a calibrated ¼" GRAS microphone on one side of the tube and the microphone to be tested directly opposing the calibrated microphone on the other side of the tube. In order to measure frequency response, sound pressure across the frequency range of interest excites both the calibrated microphone and the microphone to be tested and the output of the microphone to be tested is compared to that of the calibrated microphone. This plane wave system is placed in a sound isolation chamber so frequency response and noise can both be measured in succession. The noise was measured at ambient pressure and in vacuum in order to separate sources of acoustic and electrical noise.

RESULTS AND DISCUSSION

The measured microphone frequency response is shown in Fig. 4. The microphone sensitivity at 1 kHz is -42 dB re 1 V/Pa. For this plot, the gain of the electronics has been removed so the sensitivity is that of the MEMS transducer itself. The microphone response is relatively flat from 100 Hz to 8 kHz with a resonance frequency around 12 kHz. This response is suitable for many applications, especially those targeting voice.

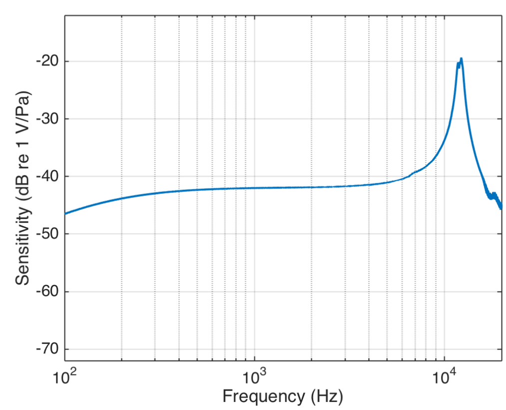

Figure 4: Frequency response of a piezoelectric MEMS microphone. This microphone ha a sensitivity of -42 dB re 1 V/Pa.

The microphone noise spectrum at ambient pressure can be seen in Fig. 5. This noise spectrum contains noise due to both electrical noise as well as acoustic noise. In order to separate the two, the microphone is measured in vacuum. Because this microphone has a resonance below 20 kHz, the vacuum measurements of this microphone show a peak in the A-weighting band due to mechanical thermal noise and lack of complete vibration isolation. Therefore, the A-weighted noise of this microphone in vacuum is not purely a measure of electrical noise. For this reason, a microphone with the same capacitance but a higher resonance frequency is used for the vacuum measurement. This vacuum measurement is also shown in Fig. 5. Similar to the plot of sensitivity, the gain of the electronics is removed so all noise is referred to the output of the MEMS transducer (i.e. the input of the ASIC).

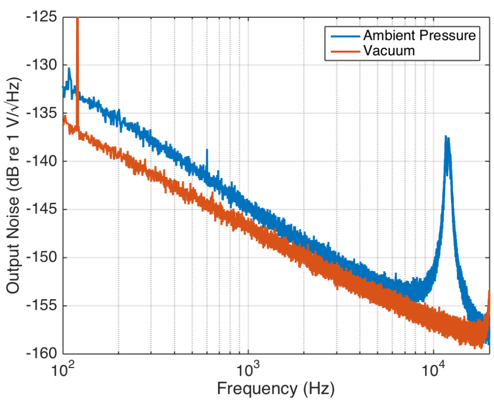

Figure 5: Output noise of a piezoelectric MEMS microphone. The A-weighted output noise at ambient pressure is -108 dBV and that in vacuum in -111 dBV.

The A-weighted output noise of the microphone, integrated from 20 Hz to 20 kHz is -108 dBV. The A-weighted output noise in vacuum is -111 dBV. Because noise sources are uncorrelated, two identical noise sources will have a total noise that is 3 dB above the noise of a single source. The 3 dB difference between the electrical noise measurement and the total noise indicates that the electrical noise and the acoustic thermal noise are at approximately equal levels in this microphone. With a sensitivity of -42 dB re 1 V/Pa and a noise floor of -108 dBV, the SNR is 66 dB.

The electrical noise can further be divided into electrical noise from the MEMS transducer and that from the ASIC. While it is difficult to separate these experimentally, the modeled ASIC noise is -117 dB and that of the MEMS transducer is -112 dB. The electrical noise in the MEMS transducer comes from the dissipation factor of the AlN film. When added together, these provide a total noise of -111 dB, which is in agreement with the measurement.

Although this microphone does not have squeeze film damping, the acoustic thermal noise is still significant. This is primarily because the resonance frequency is below 20 kHz. This resonance, therefore, amplifies the noise in the A-weighting band. In order to improve the frequency response and noise floor of the microphone, a filter can be added to the microphone to flatten the frequency response. An analog notch filter has been added to the circuitry, which allows the microphone sensitivity to be unchanged through most of the band but attenuates the resonance peak. The frequency response of the microphone with and without this filter can be seen in Fig. 6.

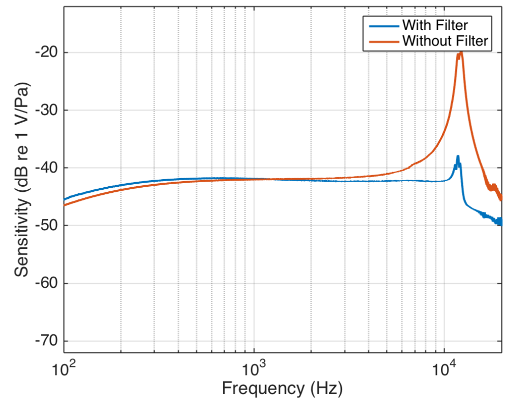

Figure 6: Frequency response of a piezoelectric MEMS microphone with and without a filter to attenuate the resonance peak.

This filter not only helps to create a more flat frequency response, but also reduces the impact of resonance on the microphone noise. The output noise with and without the filter can be seen in Fig. 7. With the filter, the A-weighted output noise decreases from -108 dBV to -110 dBV. Because the sensitivity at 1 kHz is unchanged and the noise is reduced by 2 dB, the microphone with this filter has a SNR of 68 dB.

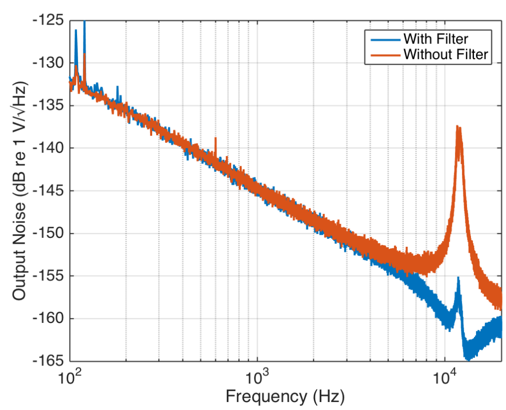

Figure 7: Output noise of a piezoelectric MEMS microphone with and without a filter to attenuate the resonance peak. With the filter, the A-weighted noise floor drops from -108 dBV to -110 dBV.

Table 1 shows performance levels of several piezoelectric MEMS microphones. Because sensitivity and SNR can be improved by building larger microphones, the sensing element area has also been included in this comparison. Much of the earlier work on piezoelectric MEMS microphones used ZnO as the piezoelectric film. More recently, however, AlN has become widely used in FBAR devices, leading to improved physical vapor deposition (PVD) techniques for AlN. The piezoelectric MEMS microphone development over the past ten years has benefitted from these film improvements [17].

Table 1: Performance overview of piezoelectric MEMS microphones.

Author	Matl.	Sensing Element Area (mm^2)	Sensitivity (mV/Pa)	SNR (A-weighted, dB)
Royer et al. 1983 [11]	ZnO	7.1	0.25	28
Franz et al. 1988 [18]	AlN	0.72	0.025	24
Kim et al. 1991 [19]	ZnO	9.2	1.0	43
Ried et al. 1993 [20]	ZnO	6.3	0.92	37
Kressman et al. 1996 [21]	PVDF	1.0	0.21	39
Fazzio et al. 2007 [22]	AlN	0.38	N/R	34
Littrell 2009 [13]	AlN	0.62	1.82	57
Williams 2011 [12]	AlN	0.54	0.039	19
This work	AlN	0.96	7.9	66, 68*

* With frequency response equalization circuit

CONSLUSIONS

Piezoelectric MEMS microphones have been a topic of research for more than 30 years. Over that time, improvements to piezoelectric MEMS microphone design, piezoelectric materials, and piezoelectric material film deposition have enabled significant improvements in performance. Much of the recent work in piezoelectric MEMS microphones has focused on their use in aeroacoustic applications because of their environmental robustness and ability to handle high sound pressure levels [12]. However, piezoelectric MEMS microphones are also capable of achieving high SNR and are, therefore, appropriate for a wide range of consumer and industrial applications as well.

This work demonstrates the highest sensitivity and highest SNR piezoelectric MEMS microphones reported in the literature. Not only is the SNR better than other piezoelectric MEMS microphones reported, but this SNR is on par with or better than capacitive MEMS microphones on the market today. This SNR along with the improved environmental robustness of piezoelectric MEMS microphones makes them especially well suited to array applications where environmental contaminants could cause other microphones to become unmatched over time.

REFERENCES

[1] IHS, "Apple Products are Driving Market Growth for MEMS Microphones, IHS Says", Press Release (2016).

[2] I. Tashev, "Beamformer Sensitivity to Microphone Manufacturing Tolerances," Proceedings of Nineteenth International Conference Systems for Automation of Engineering and Research SAER 2005, Microsoft Research, Redmond (2005).

[3] T. A. Powers and V. Hamacher, "Three Microphone Instrument is Designed to Extend Benefits of Directionality," The Hearing Journal, 55, 10 (2002), pp. 38, 40-42, 44-45.

[4] Knowles, "Knowles History" www.knowles.com/eng/Our-company/Knowles-history

[5] www.aactechnologies.com

[6] W. Conklin, "Leveraging Microelectromechanical Microphones Inherent Matching to Reduce Noise Using Multiple Microphone Elements," Proceedings of Meetings on Acoustics, 19, Knowles Electronics, Itasca (2013).

[7] Akustica, "Akustica Announces Two New High Performance Microphones," Press Release (2015).

[8] S. Conti, B. Vigna, M. F. Cortese, "Assembly of a Capacitive Acoustic Transducer of the Microelectromechanical Type and Package Thereof," Patent US8433084 (2009).

[9] F. Reining, "Microphone," Patent Application US20130051598 (2010).

[10] T. Goida, "Reduced Footprint Microphone System with Spacer Member Having Through-Hole," Patent Application US20120027234 (2010).

[11] M. Royer, J. O. Holmen, M. A. Wurm, and O. S. Aadland, "ZnO on Si Integrated Acoustic Sensor," Sensors and Actuators, 4 (1983), pp. 357 – 362.

[12] M. D. Williams, "Development of a MEMS Piezoelectric Microphone for Aeroacoustic Applications," PhD thesis, University of Florida (2011).

[13] R. Littrell, "High Performance Piezoelectric MEMS Microphones," PhD thesis, University of Michigan (2009).

[14] M. Winter, G. Feiertag, A. Leidl, and H. Seidel, "Influence of a Chip Scale Package on the Frequency Response of a MEMS Microphone," Microsyst Technol, 16 (2010), pp. 809-815.

[15] A. H. Benade, "On the Propagation of Sound Waves in a Cylindrical Conduit," The Journal of the Acousical Society of America, 44, 2 (1968), p. 616.

[16] R. Littrell and K. Grosh, "Modeling and Characterization of Cantilever-Based MEMS Piezoelectric Sensors and Actuators," Journal of Microelectromechanical Systems, 21, 2 (2012), pp. 406 – 413.

[17] G. Piazza, V. Felmetsger, P. Muralt, R. H. Olsson III, and R. Ruby, "Piezoelectric Aluminum Nitride Thin Films for Microelectromechancial Systems," Materials Research Society, 37 (2012), pp. 1051 – 1061.

[18] J. Franz, "Functionsweise und Technishe Realisierung eines Piezoelektrischen Siliziumsensors fur Akustiche Grossen," VDI-Berichte, 677, 299 (1988).

[19] E. S. Kim, J. R. Kim, and R. S. Muller, "Improved IC-compatible Piezoelectric Microphone and CMOS Process," Proceedings of 1991 International Conference on Solid State Sensors and Actuators, 270 (1991).

[20] R. P. Ried, E. S. Kim, D. M. Hong, and R. S. Muller, "Piezoelectric Microphione with On-chip CMOS Circuits," Journal of Microelectromechanical Systems, 2, 111 (1993).

[21] R. Kressman, G. Hes, and R. Schellin, "New Results for Micromachined Silicon Subminiature Microphones using Piezoelectric Polymer Layers," International Symposium on Electrets, 1044 (1996).

[22] R. S. Fazzio, T. Lamers, O. Buccafusca, A. Goel, and W. Dauksher, "Design and Performance of Aluminum Nitride Piezoelectric Microphones," 14th International Conference on Solid State Sensors, Actuators and Microsystems, U632 (2007).

CONTACT

*Robert Littrell; rlittrell@vespermems.com