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Compliant Membranes for the Development of a MEMS Dual-Backplate Capacitive Microphone using the SUMMiT V Fabrication Process

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ABSTRACT

The objective of this project is the investigation of compliant membranes for the development of a MicroElectrical Mechanical Systems (MEMS) microphone using the Sandia Ultraplanar, Multilevel MEMS Technology (SUMMiT V) fabrication process. The microphone is a dual-backplate capacitive microphone utilizing electrostatic force feedback. The microphone consists of a diaphragm and two porous backplates, one on either side of the diaphragm. This forms a capacitor between the diaphragm and each backplate. As the incident pressure deflects the diaphragm, the value of each capacitor will change, thus resulting in an electrical output. Feedback may be used in this device by applying a voltage between the diaphragm and the backplates to balance the incident pressure keeping the diaphragm stationary.

The SUMMiT V fabrication process is unique in that it can meet the fabrication requirements of this project. All five layers of polysilicon are used in the fabrication of this device. The SUMMiT V process has been optimized to provide low-stress mechanical layers that are ideal for the construction of the microphone’s diaphragm. The use of chemical mechanical polishing in the SUMMiT V process results in extremely flat structural layers and uniform spacing between the layers, both of which are critical to the successful fabrication of the MEMS microphone.

The MEMS capacitive microphone was fabricated at Sandia National Laboratories and post-processed, packaged, and tested at the University of Florida. The microphone demonstrates a flat frequency response, a linear response up to the designed limit, and a sensitivity that is close to the designed value. Future work will focus on characterization of additional devices, extending the frequency response measurements, and investigating the use of other types of interface circuitry.

ACKNOWLEDGEMENT

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CONTENTS

FIGURES

TABLES

NOMENCLATURE

CMP	chemical mechanical polishing
DRIE	deep reactive ion etch
EPNL	effective perceived noise level
FAA	Federal Aviation Administration
MEMS	MicroElectroMechanical Systems
SEM	scanning electron microscopy
SNL	Sandia National Laboratories
SPL	sound pressure level
SUMMiT V	Sandia Ultraplanar Multilevel MEMS Technology

PROJECT DESCRIPTION

The objective of this project is the investigation of compliant membranes for the development of a MEMS microphone using the Sandia Ultraplanar Multilevel MicroElectroMechanical Systems (MEMS) Technology (SUMMiT V) fabrication process. The microphone is a dual-backplate capacitive microphone utilizing electrostatic force feedback. The microphone consists of a diaphragm and two porous backplates, one on either side of the diaphragm. This forms a capacitor between the diaphragm and each backplate. As the incident pressure deflects the diaphragm, the value of each capacitor will change, resulting in an electrical output. Feedback may be used in this device by applying a voltage between the diaphragm and the backplates. This voltage creates an electrostatic force, which balances the incident pressure keeping the diaphragm stationary.

The fabrication of this device presents some challenges. First, three independent conducting layers must be fabricated to construct the diaphragm and the two backplates. The diaphragm should be compliant to increase the sensitivity of the device. The thickness of the gap between the plates, as well as the thickness of the plates themselves, must be uniform and well controlled.

The SUMMiT V fabrication process is unique in that it can meet the fabrication requirements of this project. All five layers of polysilicon are used in the fabrication of this device; poly0 is used for electrical connections, poly1 and poly2 are combined to form the lower backplate, poly3 is used for the diaphragm, and poly4 is used for the top backplate. The SUMMiT V process has been optimized to provide low-stress mechanical layers that are ideal for the construction of the microphone’s diaphragm. Perhaps the greatest advantage of the SUMMiT V process is the use of chemical mechanical polishing (CMP). The use of CMP results in extremely flat structural layers and uniform spacing between the layers, both of which are critical to the successful fabrication of the MEMS microphone.

INTRODUCTION AND MOTIVIATION

In an effort to reduce the impact of airports and air travel on local communities, the Federal Aviation Administration (FAA) has regulated the level of noise that aircraft may radiate. The US Code of Federal Regulations specifies the tests that an aircraft must pass for its airworthiness certification. The requirements are specified for three general classes of aircraft and are broken down further by weight. The regulations for each class of aircraft specify the maximum allowable effective perceived noise level (EPNL). The EPNL is the measured noise level corrected for atmospheric conditions, the duration of the sounds, and the specific operating conditions of the jet engine(s). For example, for an aircraft weighing 617,200 pounds or more, the most stringent requirement limits the noise during approach to 105 EPNdB. [1]

In order to meet these requirements, the noise radiation of an aircraft must be considered during its design. In order for engineers to design quieter aircraft, it is important to localize and understand the sources of noise generation. The behavior of airframes and jet engines can be studied by conducting measurements on scale models in a wind tunnel, where conditions are well controlled. [2] Aeroacoustic measurements are performed to quantify the sound field and to provide insight into the noise generation mechanisms so that the noise can be reduced to acceptable levels. A key component in any aeroacoustic measurement setup is the microphone. The performance characteristics of the selected microphone greatly impacts the success of the measurements and the quality of the results. Some of the characteristics of the microphone to consider are the dynamic range, sensitivity, bandwidth, stability, size, and cost. [2]

A microphone must meet several requirements to be suitable for aeroacoustic measurements. Table 1 summarizes how the requirements for aeroacoustic measurements differ from audio measurements. An aeroacoustic microphone should be capable of operating up to sound pressure levels (SPLs) of 160 dB due to the high SPLs radiated by jet engines. Furthermore, the frequency range of interest for aeroacoustic measurements extends up to 90 kHz because experiments are often conducted on scale models. For this comparison, a dynamic range of 100 dB is assumed. In order to have diffraction-free measurements at high frequencies, the microphone size must be small; at 90 kHz, the microphone radius should be less than 0.6 mm. MEMS microphones are well suited for this application because of the desired small size and high-frequency range.

Table 1. Comparison of audio and aeroacoustic microphone specifications.

Property	Audio Microphone	Aeroacoustic Microphone
Maximum Pressure	120 dB	160 dB
Bandwidth	20 Hz – 20 kHz	45 Hz – 90 kHz
Noise Floor	20 dB	60 dB
Maximum Radius	2.7 mm	0.6 mm

BACKGROUND

A microphone is a transducer that converts an acoustic signal into an electrical signal. Figure 1 shows a schematic representation of a generic microphone. Most microphones share some common traits with each other. They have a diaphragm that is exposed to the incident sound pressure. The sound pressure acts on the diaphragm and causes it to deflect. The deflection is detected by a transduction mechanism and an electrical output is generated. Microphones also have a vent channel to provide pressure equalization to the cavity. The vent channel causes the microphone to respond only to time-varying pressures. This distinguishes a microphone from an absolute pressure sensor that measures static pressures.

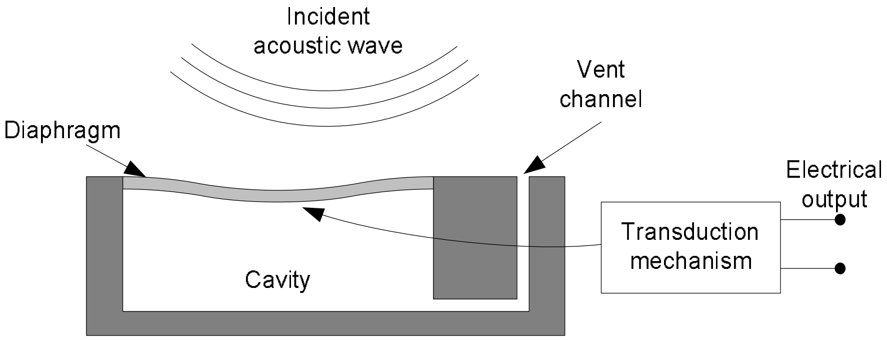

Figure 1. Illustration of the operation of a microphone. The incident pressure causes a diaphragm deflection, which produces an output voltage.

There are several transduction schemes that have been implemented in MEMS microphones; these include piezoelectric, piezoresistive, optical, and capacitive. [3] Each of these transduction techniques has advantages and disadvantages for aeroacoustic applications. Piezoelectric microphones have the potential for a high sensitivity and a low noise floor. In addition, they do not require a power supply to operate. However, the fabrication of piezoelectric microphones typically uses materials that are incompatible with standard fabrication technologies [4]. Optical microphones offer immunity from electromagnetic interference at the point of transduction. In addition, they can be deployed in environments too harsh for other microphone technologies. [5] However, optical microphones require an elaborate optical setup and optoelectronics to convert the optical signal to an electrical signal. Piezoresistive microphones can be very robust; in addition, their performance does not suffer due to parasitic capacitance. However, they tend to suffer from low sensitivities, temperature drift, and inherent flicker noise. [6] Capacitive microphones typically have high sensitivity and a low noise floor, but they can be affected by parasitic capacitance. [7]

MEMS-based aeroacoustic microphones have been developed using each of the above transduction schemes. The performance specifications of these previous MEMS microphones are shown in Table 2. The optical microphone has the highest bandwidth but it has the lowest dynamic range. The piezoelectric and piezoresistive microphones have similar specifications; however, the piezoelectric microphone has the edge in terms of both dynamic range and bandwidth. Existing capacitive microphones possess a large dynamic range; however, they cannot measure up to 160 dB and their bandwidth is much too small for aeroacoustic measurements [9].

Table 2. Comparison of previous aeroacoustic microphones.

Specification	**Piezoelectric [4]**	**Piezoresistive [6]**	**Optical [8]**	**Capacitive [9]**
Radius	900 µm	500 µm	500 µm	1.95 mm
Max. Pressure	169 dB	160 dB	132 dB	141 dB
Theoretical Bandwidth	100 Hz – 50.8 kHz	10 Hz – 40 kHz	300 Hz – 100 kHz	251 Hz – 20 kHz
Noise Floor	48 dB/rt. Hz	52 dB/rt. Hz	70 dB/rt. Hz	23 dBA

In the work, a dual-backplate capacitive microphone was developed at the University of Florida, fabricated using the SUMMiT V process at Sandia National Laboratories (SNL), and post-processed at the University of Florida. The fabrication and characterization of this device will be discussed. The experimental calibration compares favorably to previous MEMS-based aeroacoustic microphones.

DEVICE OPERATION

A cross section of the dual-backplate microphone is shown in Figure 2. The major elements of the microphone are the diaphragm, top backplate, bottom backplate, air gaps, backplate holes, cavity, and the vent channel. The diaphragm is located between the two backplates; the three plates are separated by two air gaps. The backplates have holes to allow the acoustic pressure to pass through the backplates and deflect the diaphragm. A cavity is created beneath the microphone structure. A vent channel connects the cavity to the incident pressure. This equalizes the pressure in the cavity and limits the low-frequency response of the microphone.

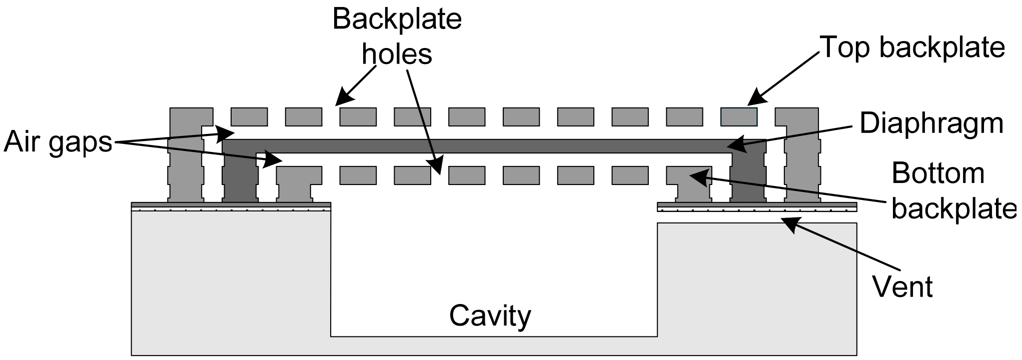

Figure 2. Schematic cross section of the dual-backplate microphone showing the key elements.

The diaphragm and both backplates are constructed out of a conducting material. Thus two capacitors are formed, one between the diaphragm and each backplate. The incident pressure passes through the top backplate and deflects the diaphragm. This deflection causes a change in the capacitance values that is detected by the interface circuitry. As the diaphragm deflects, the air in the cavity compresses; this effectively loads the diaphragm. A small cavity will offer more resistance to the diaphragm motion; thus it is desirable to design the microphone with a large cavity to prevent a loss in sensitivity.

A convenient technique to analyze the behavior of the microphone is lumped element modeling. If the acoustic wavelength is much larger than the size of the microphone, then the distributed properties of the microphone can be represented by a set of lumped elements. By analyzing the storage and dissipation of energy in the microphone structure, an equivalent circuit model (or lumped element model) of the microphone can be constructed. The lumped element model of the dual-backplate microphone is given in Figure 3. The diaphragm is represented by a mass and compliance. Each backplate is represented by a resistance due to losses in the air gaps and backplate holes. The cavity is modeled as a compliance and the vent channel adds a resistance to the model. Using the lumped element model, the predicted frequency response of the microphone can be found.

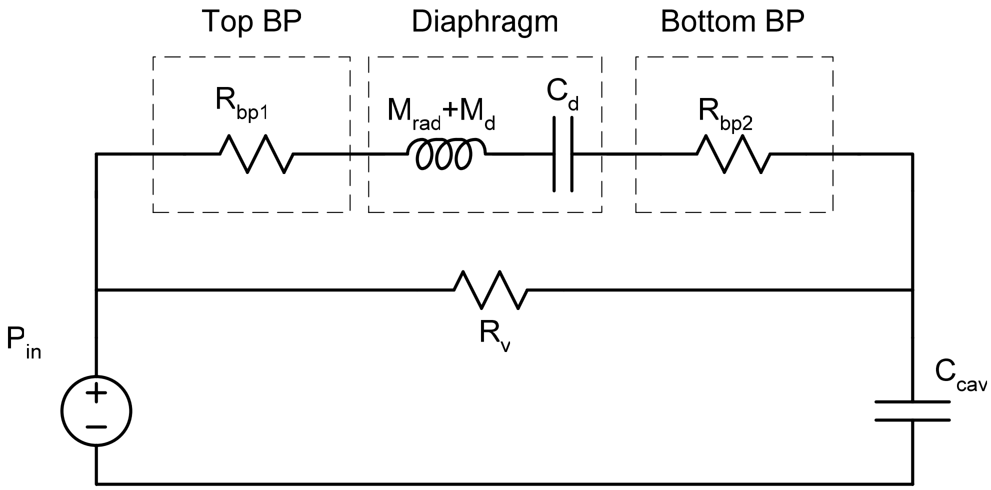

Figure 3. Lumped element model of the dual-backplate microphone.

FABRICATION

The SUMMiT V process at SNL was used to fabricate the structural layers of the microphone. This process mainly consists of the deposition and patterning of alternating layers of polysilicon and silicon dioxide. Polysilicon is used to form the microphone structure and the silicon dioxide is a temporary, or sacrificial, material to support the various layers of polysilicon during fabrication. After completion of the SUMMiT V process, a series of post-processing steps are performed to release the device and complete the fabrication.

The process flow for the dual-backplate capacitive microphone is shown in Figure 4. The SUMMiT V process begins with a 6-in. silicon wafer. A layer of silicon dioxide and silicon nitride are then deposited. These insulate the polysilicon structure from the silicon substrate. In addition, the silicon nitride is used to provide good adhesion for the polysilicon layers. The first layer of polysilicon, poly0, is then deposited. This polysilicon layer is used to form a base for the anchors and for electrical interconnections. A 2-µm layer of sacrificial oxide forms a spacer between the poly0 electrical connections and the next layer of polysilicon. The bottom backplate is formed by depositing and patterning poly2. The bottom air gap space is held by the next sacrificial layer, sacox3. The diaphragm is then formed from poly3. The final steps of the SUMMiT V process create the top backplate.

The microphone was returned from SNL in the form of unreleased die. The remainder of the processing was conducted at the University of Florida; the key post-processing steps are also shown in Figure 4. To facilitate processing an individual die, a 4-in. handle wafer was constructed to hold the microphone die. The handle wafer consists of a silicon wafer joined to a Pyrex wafer. A cavity was etched in the silicon wafer to hold the microphone die. Pyrex is used for the lower layer because this layer must be transparent for front-to-back alignment. The first step of the post-processing is to remove layers of oxide and polysilicon from the backside of the microphone chip. This is accomplished via mechanical lapping. Then the silicon substrate below the microphone structure is etched using a deep reactive ion etch (DRIE). This is followed by two etches to remove the thin layers of oxide and nitride. Finally, the sacrificial oxide is removed to release the microphone structure. To avoid stiction, the microphone is dried using supercritical CO_2. This completes the microphone fabrication.

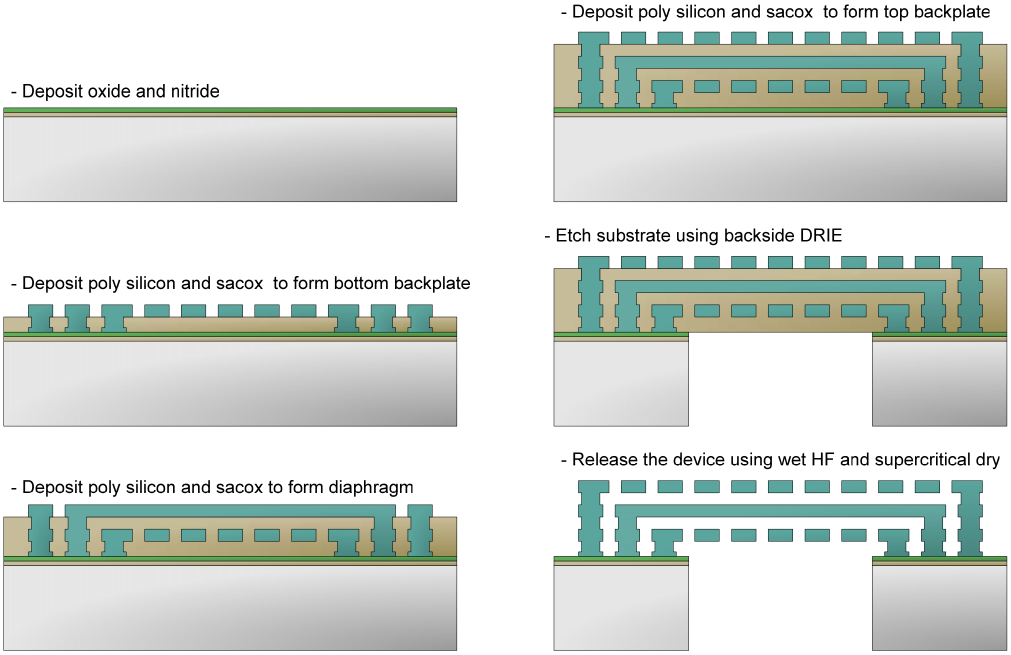

Figure 4. Fabrication process for the dual-backplate capacitive microphone.

RESULTS

The dual-backplate microphone has been designed and fabricated. Shown in Figure 5 are two images of the microphone; on the left is a photograph of the top of the microphone and on the right is a scanning electron microscopy (SEM) image showing the three structural layers of the microphone. Preliminary characterization of the device shows that it is well suited for aeroacoustic measurements. Figure 6 shows the microphone output voltage plotted versus incident pressure; this demonstrated a linear response up to 160 dB. The frequency response of the microphone is plotted in Figure 7. The frequency response is flat up to 20 kHz, which was the limit of the experimental setup. The resonant frequency was found to be 230 kHz, as shown by Figure 8. The frequency response should extend up to near the resonant frequency. The input referred pressure noise spectrum is shown in Figure 9. At a frequency of 1 kHz, the equivalent pressure noise is 42 dB/rt. Hz. The interface circuitry is the dominant source of low-frequency noise; improvements to the interface circuitry could lower the noise floor. At 1 kHz, the microphone has a dynamic range of 42 dB to 160 dB for a 1-Hz bin. The microphone specifications are listed in Table 3.

Table 3. Specifications of the dual-backplate capacitive microphone.

Specification	**Value**
Dynamic range at 1 kHz (1-Hz bin)	160 dB
Measured bandwidth	300 Hz – 20 kHz*
Measured resonant frequency	230 kHz

* Limited by measurement setup. The bandwidth should extend to the first resonance at 230 kHz.

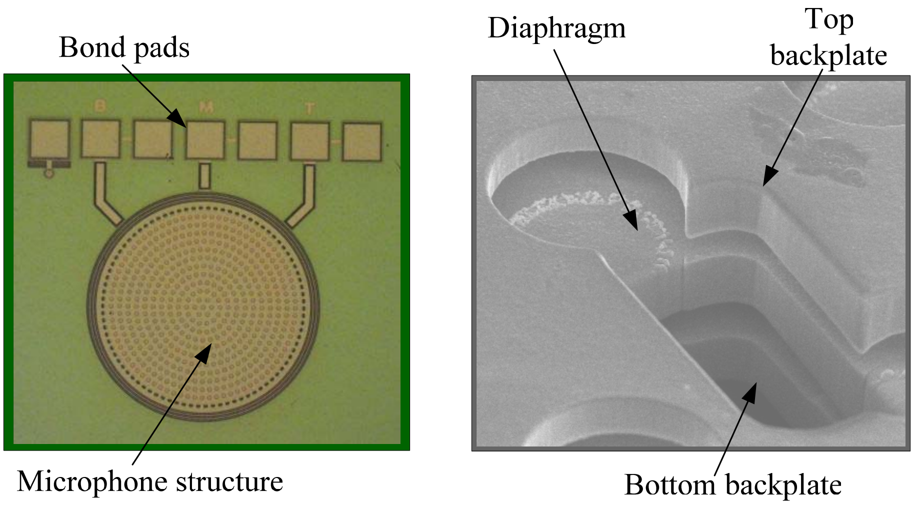

Figure 5. Images of the fabricated dual-backplate microphone.

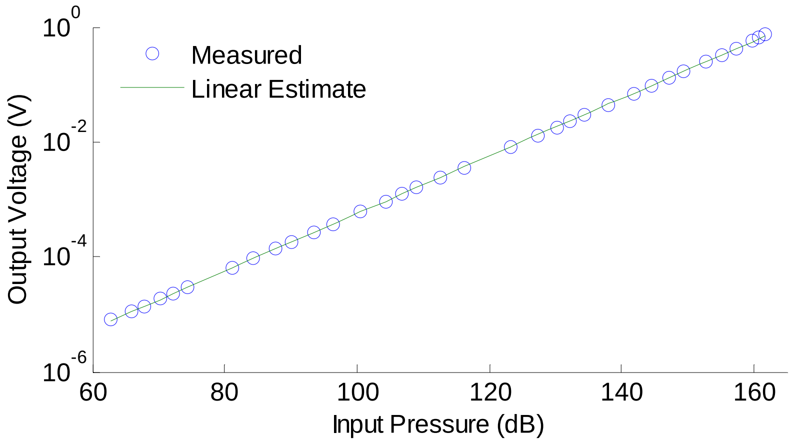

Figure 6. Microphone output voltage plotted versus incident pressure showing a linear response up to 160 dB.

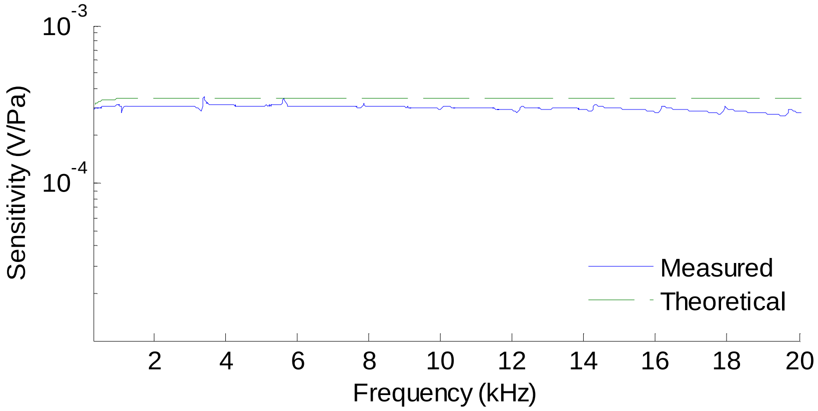

Figure 7. Microphone output voltage plotted versus frequency showing a flat frequency response up to 20 kHz.

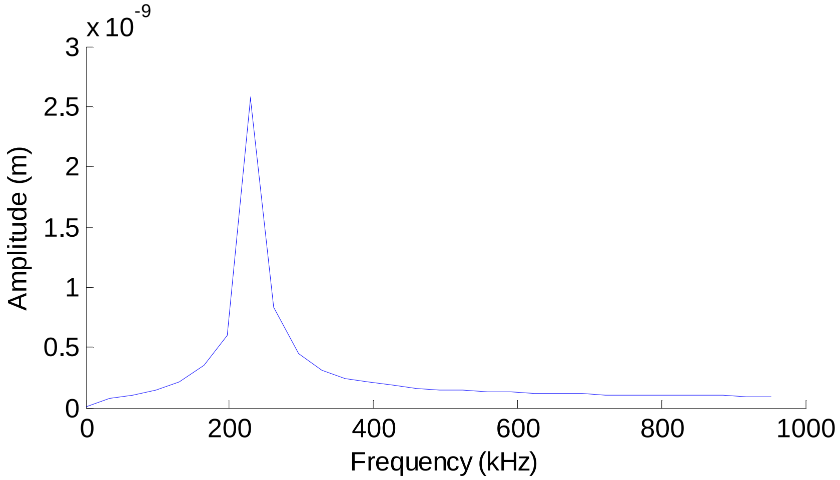

Figure 8. Experimentally measured resonant frequency.

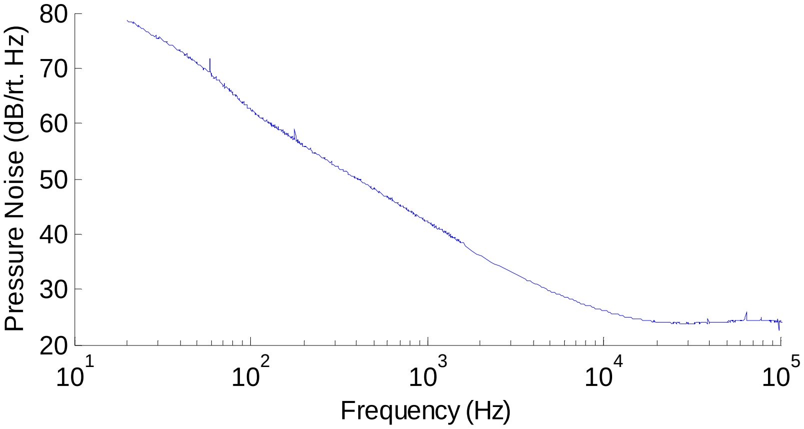

Figure 9. Input referred pressure noise spectrum.

SUMMARY

The MEMS capacitive microphone has finished fabrication at SNL and has been post-processed at the University of Florida. The microphone has been packaged and has completed initial testing. The microphone demonstrates a flat frequency response, a linear response up to the designed limit, and a sensitivity which is close to the designed value. Future work will focus on characterization of additional devices, extending the frequency response measurements, and investigating the use of other types of interface circuitry. SNL has been an essential partner in this project by providing access to and training for the SUMMiT V process.

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