

The Design, Fabrication and Characterization Of A Novel Miniature Silicon Microphone Diaphragm

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ABSTRACT

A novel miniature silicon microphone diaphragm is described that is highly robust when subjected to stresses that may arise during the fabrication process. The novel diaphragm is composed of a reinforced plate supported on carefully designed hinges. The overall dimension of the polysilicon diaphragm is 1mm by 1mm by 40 microns. The measured response of the diaphragm closely resembles that of an ideal rigid plate over a frequency range extending well beyond the audible range. This approach leads to a structure that is remarkably robust and tolerant of the stresses that have plagued efforts to fabricate miniature microphones [1]. Potential applications include advanced consumer products such as cell phones, portable digital devices, and camcorders.

Keywords: MEMS, silicon microphone, stress, miniature diaphragm, fabrication

1 INTRODUCTION

Residual stress produces major challenges in the fabrication of MEMS devices. This is particularly true in the development of MEMS microphones since the response of the thin sound-sensitive diaphragm is strongly affected by stress. Because the stress is strongly dependent on fine details of the fabrication process that are almost impossible to control sufficiently, it nearly always has significant detrimental effects on microphone performance.

Much effort has been made to control the flatness and dynamic performance of thin film diaphragms [2,3,4,5,6,7, 8]. Lee et al [9] discloses a method to fabricate a micromachined pressure transducer having a multi-layer silicon nitride thin film cantilever diaphragm. The technique relies on the symmetry of the stress gradient in the two outer layers and a larger tensile stress (250 MPa) in the second layer to maintain diaphragm flatness. The measured static deflection due to stress is more than 15 microns. This static deflection makes this design unacceptable for miniature capacitive microphones that require a small gap between the diaphragms and backplates. Loeppert et al. [10] discloses a cantilever center support diaphragm design. A corrugated structure and a sandwich of two quilted films separated by a thin 23 micron sacrificial layer are employed to match the

diaphragm compliance to the desired pressure range as well as to counter any curling tendency of the diaphragm. It can be difficult to control the flatness with this approach. A patent by Bernstein [11] discloses a structure consisting of a single crystal silicon diaphragm supported on its corners by patterned silicon springs. By supporting the diaphragm only at the corners, it is possible to increase the diaphragm compliance, and subsequently, the sensitivity to sound. This approach permits a design that is more compliant than the usual approach where the diaphragm is supported entirely around its perimeter. However, it does not ensure that the stresses in the structure will not result in breakage (if the stress is tensile).

2 DESIGN AND FABRICATION

2.1 Diaphragm Design

A robust microphone diaphragm design is presented that maintains good dimensional control under the influence of residual stress, either compressive or tensile, while having its dynamic response dominated by only a single mode of vibration.

This design uses a stiffener-reinforced membrane that is supported on specially designed torsional springs that have very high stiffness in the transverse direction but well controlled stiffness in torsion. The result is a lightweight structure that acts like a rigid plate with a flexible pivot support along one edge. Figure 1 displays the overall dimensions of the diaphragm. The light green represents the 4-micron thick stiffeners that extend 40 microns out of the diaphragm plane. The length of the torsional springs is 10 microns, which has been chosen to tune the structural stiffness such that the frequency of the first mode is around 24 kHz [1].

2.2 Diaphragm Fabrication

The diaphragm fabrication starts with a deep trench etch into the silicon wafer that acts as a mold for the thick polysilicon ribs, followed by sacrificial wet oxide growth and the polysilicon deposition. The oxide layer acts as an etch stop for the backside cavity etch and it also keeps the fragile microphone diaphragm from being fully released following the backside cavity etch. The oxide will hold the membrane firmly in place until it is etched away during the

final step. The polysilicon that fills the trenches will become the supporting ribs, and the polysilicon on the surface of the wafer will form the microphone diaphragm or “skin”. The polysilicon film is then smoothed with either chemical mechanical polishing or a reactive ion etch. The next step is the backside cavity etch that defines the air chamber behind the microphone diaphragm. The wafer is diced into microphone chips before the final microphone diaphragm release. The microphone diaphragm is then fully released at the chip level by dissolving the sacrificial oxide layer in hydrofluoric acid. Figure 2 shows the fabrication process flow of the microphone diaphragm [12] and Figure 3 shows a SEM (Scanning Electron Microscope) image of the vicinity of the hinge support of the fabricated silicon microphone diaphragm.

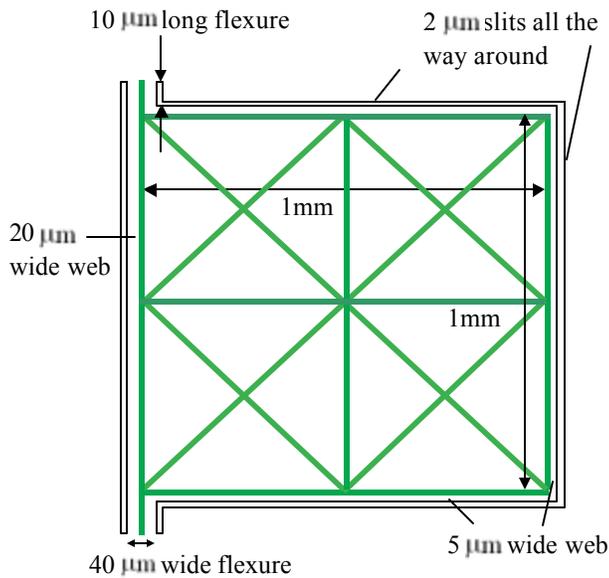


Figure 1 Dimensions of the microphone diaphragm

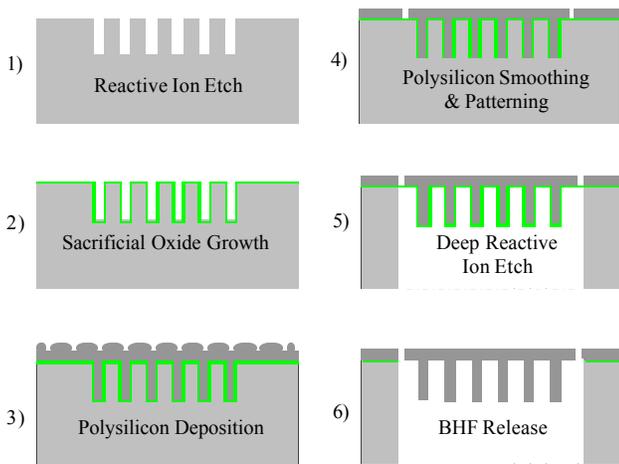


Figure 2 Diaphragm fabrication process flow

3 DIAPHRAGM CHARACTERIZATION

3.1 Test methods

An experimental setup is described that allows the acoustic response of micro-fabricated microphone diaphragms on bare die to be measured with different back volume configurations. This setup is pictured in Figure 4. A cylinder fixture with the test die is shown, along with the front lens of a laser vibrometer, a loudspeaker, reference microphone, and microscope. This equipment is mounted on a Newport Research Series vibration isolation table (RS 4000, dimensions 3'x6'x8").

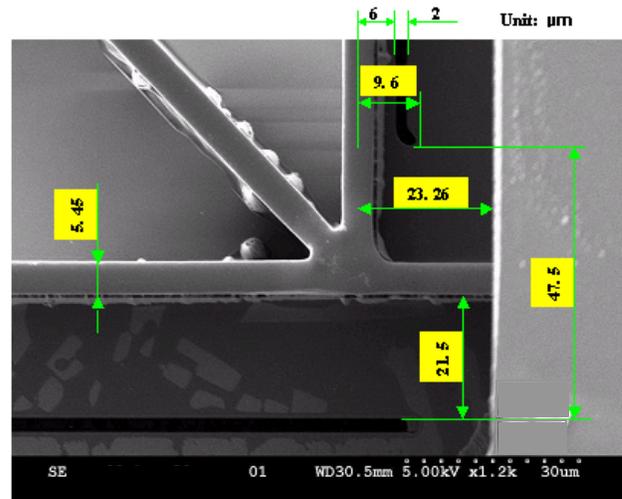


Figure 3 SEM image of the vicinity of the hinge support of the fabricated silicon microphone diaphragm

The microphone diaphragm test die is carefully taped around the edges using wafer tape to attach it to a circular disk (1.25" diameter, 0.07" thick). This disk is bolted to the end of a cylinder (1.25" OD, 0.688" ID, 5" length) that is filled with sound absorbing foam. To test the diaphragm with a large back volume, the chip is mounted to a disk with a 1/8th inch (3.175 mm) diameter hole with the test diaphragm centered over the hole, exposing the backside of the diaphragm to the inside of the test cylinder. The diaphragm is tested with a small back volume by mounting the test die on a disk without a hole, making the back volume of the diaphragm defined by the die thickness and backside cavity etch.

A laser vibrometer is used to measure the vibration at the center of the microphone diaphragm (Polytec OFV-302 sensor head with OVF-3000 vibrometer controller). For positioning of the laser spot, the vibrometer sensor head is mounted on a pair of horizontal and vertical Oriel motorized micrometers that are controlled by a joystick (Oriel Motor Mike Control, Model 18000). A dissecting microscope with a digital camera is used to monitor the location of the laser spot as it is manually positioned (Leica

Wild M3C, Kodak MDS-100 digital video camera with Optem SC38 microscope attachment). The cylinder is attached to a rotation stage and linear positioning stage to further aid in positioning the test diaphragm relative to the laser vibrometer.

A loudspeaker is placed approximately six inches from the test membrane at grazing incidence to the plane of the test die. The sound pressure generated by the loudspeaker is measured close to the test diaphragm with a 1/8th inch diameter reference microphone, positioned as shown in Figure 4 (B&K condenser microphone type 4138 with type 2670 pre-amp; B&K dual microphone supply type 5935).

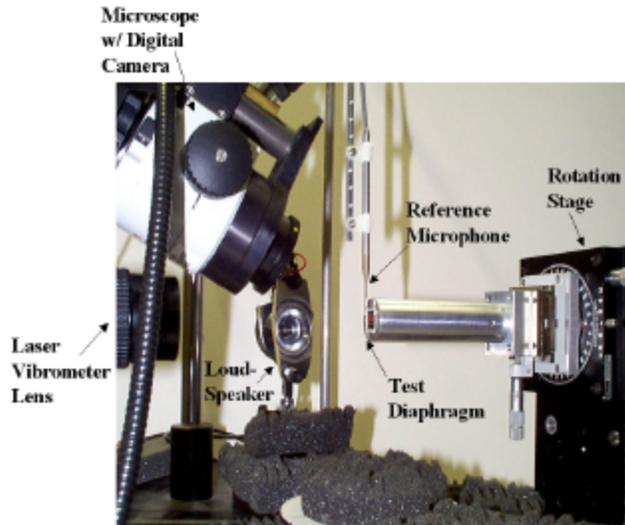


Figure 4 Test setup used to measure the response of the microphone diaphragm

A computer controlled data acquisition system is used to create the excitation signal for the loudspeaker and simultaneously measure the microphone and laser vibrometer signals (Spectral Dynamics, SigLab model 50-21). A burst chirp is sent to a power amplifier that drives the loudspeaker. Data is sampled with 16-bit resolution at 128 kHz. A custom cosine taper window is applied to the laser vibrometer and reference microphone time traces prior to spectral processing to reduce the effects of acoustic reflections. The transfer function of the laser vibrometer with respect to the reference microphone is estimated using 20 spectral averages, then processed to get the mechanical acoustic sensitivity of the diaphragm in units of [mm/Pascal].

3.2 Back Volume and Slits Effect on the Response of the Diaphragm

The small back volume significantly increases the stiffness of the system and causes the viscous flow of air through the slits that separate the diaphragm and the substrate by coupling the air in the slits with the motion of

the diaphragm, adding a significant amount of damping. An approximate model has been developed to account for the effects of the small back volume behind the microphone diaphragm and the narrow slit around its perimeter. This is based on a lumped parameter approach where the diaphragm parameters are extracted from a detailed finite element model, and the parameters for the air in the slits and back volume are calculated with theoretical equations. The low-frequency response of the diaphragm is predicted to be adversely affected by the slits and the small back volume.

Measured and predicted results are shown in Figure 5 for the response of the center of the microphone diaphragm. The figure shows nearly perfect agreement between our predictions and measurements of the frequency response. When the back volume and slits are accounted for in the model, there is a 6dB/octave roll off at low frequencies as shown in the predicted curves in Figure 5. The “small back volume” is made up of the 380 microns thick wafer. Measured data were obtained only above 1000 Hz due to the experimental set up. The model we developed does an excellent job in predicting the responses including the low-frequency cut-off effects. The prediction is based on an entirely first principles approach; the model parameters were not adjusted to get the measurements and predictions to agree.

The small back volume and the slits significantly reduce the response of the diaphragm relative to our original prediction, which neglected their effects. To offset some of this loss in sensitivity, it is possible to drill a small hole in the ceramic substrate and package to greatly increase the size of the back volume. This would bring the response much closer to our original prediction. A prediction based on increasing the depth of the back volume from 380 microns to 5000 microns is identified in the figure as “predicted large back volume.”

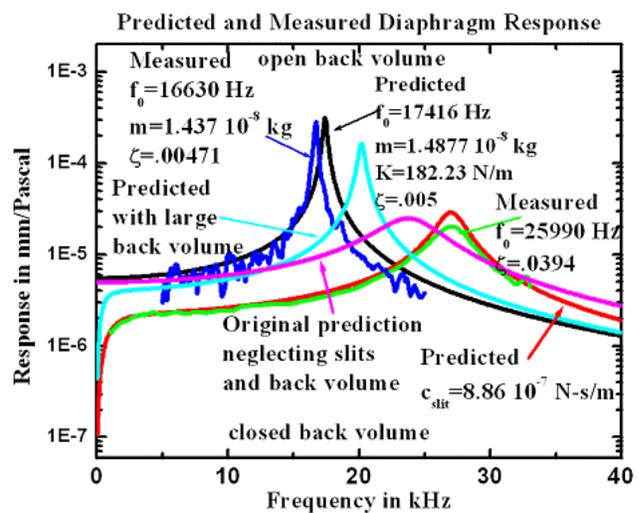


Figure 5 Predicted and measured diaphragm response

4 CONCLUSION

The design, fabrication and characterization of a novel robust microphone diaphragm are described. The results are extremely encouraging because it appears that this design is not adversely affected by intrinsic stress in the polysilicon. We have demonstrated with prototype devices that our design approach avoids the difficulties caused by stress in silicon microphones. This is accomplished by employing structural analysis and design to develop low-mass diaphragms that can withstand stresses induced both during fabrication and operation. The current fabrication results reveal that the idea of fabricating a fairly rigid structure that is supported on specially designed supports can lead to revolutionary improvements in microphone design [1]. This approach leads to a structure that is remarkably robust and tolerant of the stresses that have plagued efforts to fabricate miniature microphones.

5 ACKNOWLEDGEMENT

This work is supported by DARPA grant DAAD17-00-C-0149 (Development of Biomimetic Acoustic Microsensor) and NIH grant 5R01 DC005762-04 (Sensing and Processing for Directional Hearing Aids) from the National Institute of Deafness and Other Communication Disorders to RNM and partially supported by Binghamton University's New York State Center of Excellence in Small Scale Systems Integration and Packaging through funding from the New York State Foundation for Science, Technology and Innovation (NYSTAR) and Empire State Development Corporation (ESDC).

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