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Optical Microphone Structures Fabricated for Broad Bandwidth and Low Noise

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***Abstract*— A micromachined optical microphone structure using a grating based interferometer has been presented previously and is undergoing continued development (JASA, vol. 118, pp 3000-3009, November 2005). Two advantages of the approach that have been highlighted in prior work are high displacement resolving capability of the microphone diaphragm vibration (2 pm rms over the audio bandwidth) and a flexible mechanical design space for achieving broad bandwidth and low thermal noise designs. Here, we summarize a variety of structures we are fabricating using Sandia National Laboratories silicon-based microfabrication technology to explore this versatile design space. These structures are being packaged to resemble instrumentation-type microphones with approximately 1cm^2 form factor in order to facilitate rigorous acoustic evaluation in the Micromachined Sensors and Transducers Laboratory (MiST) and anechoic test facilities at Georgia Tech.**

I. INTRODUCTION

Most micromachined microphones have relied on detecting capacitance changes which limits the ultimate performance of a scaled down microphone since signal level is proportional to the electrode area and inversely proportional to the separation of the electrodes. As summarized by Gabrielson [1] and explored in the design of a high performance MEMS measurement microphone [2], thermal mechanical noise performance of the microphone is also coupled to these dimensions which prevents independent optimization of electrical and mechanical properties. In the micromachined optical interference microphone depicted in Fig.1 the interferometric displacement detection is decoupled from the electrical properties of the structure which allows the electrical / optical and mechanical properties to be independently optimized. In this structure, a monolithically integrated diffraction grating serves as the beam splitter in a Michelson-type interferometer, and the intensities of a zero and higher order diffraction orders are modulated by the diaphragm vibration. Fig. 2. summarizes a typical interference curve for this device (i.e. plot of a first order intensity versus applied bias potential between the grating and diaphragm) – which in this particular case was obtained using a single mode 850nm VCSEL as the light source. This structure has been described in detail previously and has undergone significant development [3-5]. Most recently, we have utilized the versatile mechanical design space to realize a variety of silicon microstructures designed for broad bandwidth acoustic detection and low thermal noise levels.

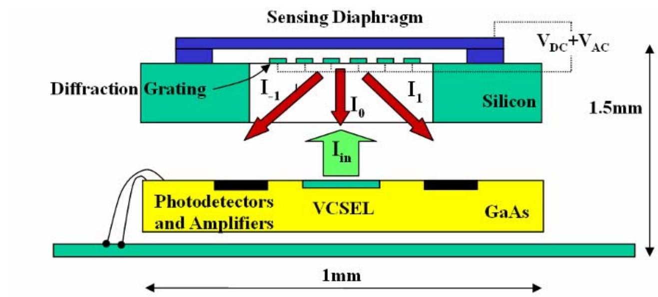

Fig. 1. Schematic of the optical displacement detection scheme. Light from the VCSEL is modulated by the diffraction grating and the reflector providing the same interference behavior and sensitivity as a Michelson interferometer. For a microphone, the top reflector is a rigidly supported membrane.

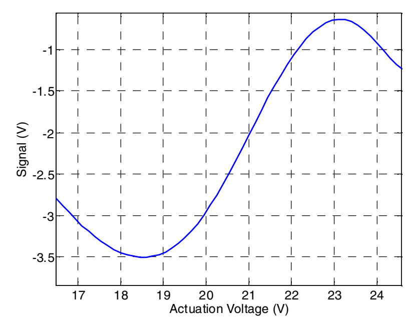

Fig. 2. Experimentally traced interference curve using a VCSEL as the light source [11]

II. MICROMACHINED DEVICES

A recent embodiment of the silicon component from Fig.1. is summarized in the 3-D models and optical images shown in Fig. 3. This structure was fabricated using the SUMMiT-lite™ process at Sandia. The membrane dimensions and clamping was varied for several design iterations to demonstrate the flexibility gained by this approach, while maintaining the same displacement sensitivity across all the designs. In the 3D cross-sections, the blue layer is a 2.25 μm thick polysilicon layer (reflector membrane), which is removed in the next image to show the details of the support arms and the grating. These features can also be seen in the micrographs which were taken from the back side of the fabricated devices.

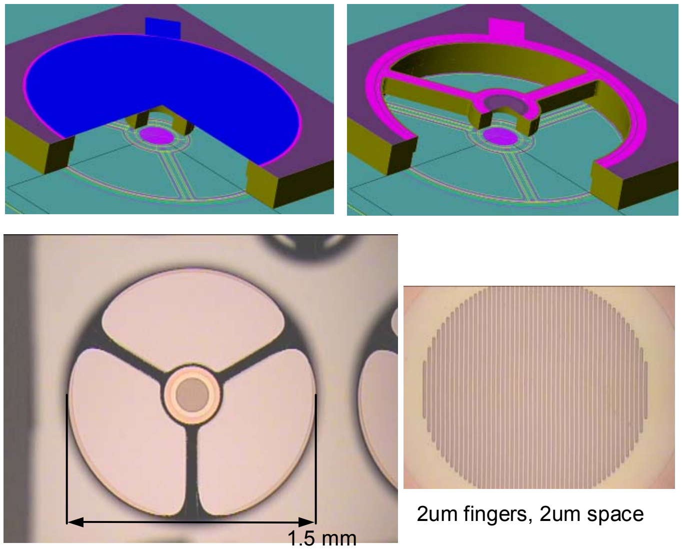

Fig. 3. 3D models and images of a microphone structure. These devices were fabricated using SUMMiT-lite™ process at Sandia National Laboratories. Images show the 50um thick silicon support arms and the details of the diffraction grating. The 2.25 um thick polysilicon membrane is behind the grating and support arms in the device pictures. Rigorous acoustic characterization of these structures in [11] shows thermal noise levels of 2.7 μPa/√Hz.

As opposed to backplate structures used in conventional MEMS capacitive microphones which consist of a repetitive pattern of small perforations or holes, this backplate is quite different and consists of mostly open area to realize low squeeze film damping and low thermal mechanical noise levels. These silicon structures were first presented in [6] where their dynamics and thermal noise characteristics are studied in detail. This 1.5 mm diameter structure has a diaphragm limited bandwidth near 20 kHz, and 2.7 μPa / √Hz thermal noise level which corresponds to an A-weighted detection noise level of 24 dB(A). Following characterization work performed in [6], the displacement resolving capabilities of the detection approach are sufficient to enable 3x (i.e. ~10 dB) improvements in these figures from continued improvements in mechanical design. We briefly summarize some of the fabrication procedures we are using to continue the exploration of this design space.

III. FABRICATION

Several different fabrication runs were performed to generate a number of device variations. Some of the devices used the standard SUMMiTV™ flow, while another set was generated using SUMMiT-lite, which is a subset of the more extensive process flow. In the simplified flow, poly0 (ground plane and electrical signal routing), sacox1 (sacrificial oxide layer, 2.5 to 6um thick) and poly1/2 (mechanical polysilicon layer, 2.25um thick) were used. Bosch etched features formed the support arms in the silicon substrate. In the full process flow, all mechanical polysilicon layers were used to form the anchor and electrical routing structures, top polysilicon layer (poly4) forms the reflector/diaphragm for the microphone. Again, Bosch etch was used to form the support arms and the cavity in the silicon substrate.

Top and back side images of the devices from the SUMMiTV™ run are shown in Fig.4. Different membrane sizes and grating support techniques were evaluated with these devices. Structures utilizing a nitride backplate with an array of circular perforations were fabricated using this process flow, with a micrograph of such a structure presented in Fig. 5. These devices more closely resemble traditional condenser microphone backplates but still utilize a relatively large degree of perforation to achieve low damping – with holes occupying more than 50% of the total area.

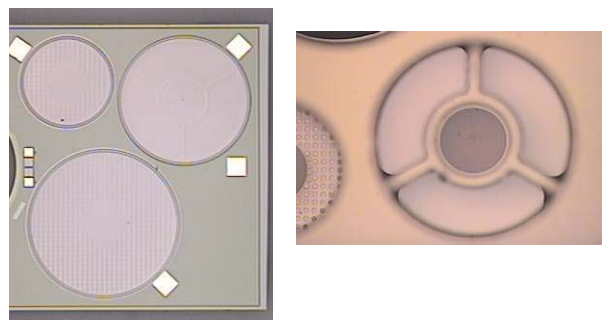

Fig. 4. Micrographs of devices fabricated in SUMMiTV™ flow. Top side image shows several design variations, back side image shows the large (400um diameter) grating and support arms for the 1.2 mm membrane diameter device.

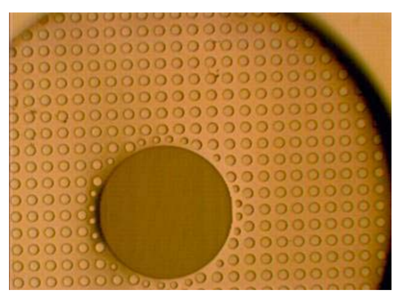

Fig. 5. Micrograph showing the backside view of a device with a nitride backplate that is perforated with a repetitive pattern of holes – more closely resembling a conventional condenser structure.

Another feature that was included in this fabrication run is a static pressure relief port on the membrane, which is seen in Fig.6. With the photolithographically defined 3um diameter ports, low frequency response of the membrane is defined more precisely, rather than relying on the sealing and venting ports in the package which would produce more variation from device to device. The size and/or number of the vent holes is a critical design parameter for high performance microphones – affecting both the lower limiting frequency in the acoustic response [7] and the low frequency thermal noise characteristics of the microphone [8]. We have fabricated structures designed to respond to below 5 Hz which is consistent with the needs of some high performance applications.

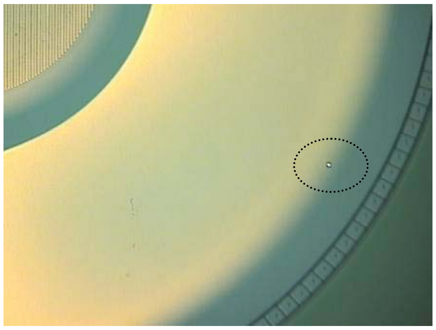

Fig. 6. 3um diameter pressure relief port on the membrane. This feature allows for more uniform low frequency response from device to device.

IV. CHARACTERIZATION

Completed devices utilizing these silicon structures are undergoing acoustic evaluation in the anechoic test facilities of the Integrated Acoustics Laboratory (IAL) at Georgia Tech. Initial microphone prototypes are designed to resemble standard instrumentation microphones to enable rigorous acoustic evaluation. Recent developments in this effort are summarized in Fig. 7 [9]. Although this package presents an approximate 1cm diameter acoustic form factor, the essential optoelectronic components are contained within a sub-mm^3 volume [10]. The electrostatic frequency response of the 1.2 mm diameter device depicted in Fig. 4 is presented in Fig. 8a. Here, electrostatic actuation features of the device have been used which provide a convenient way to generate broadband pressures for characterization purposes. This device shows a flat frequency response up to a first resonance observed near 30 kHz. The smaller devices presented in Fig. 4 have beyond 50 kHz diaphragm resonance and may be useful for high frequency applications.

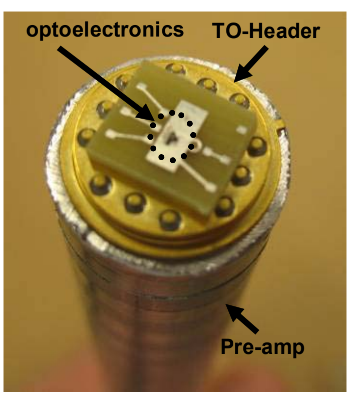

Fig. 7 Photograph of a microphone prototype [9] with approximately 1cm diameter and made to resemble an instrumentation-type microphone to facilitate head-to-head acoustic evaluation. The essential optoelectronics are contained with a sub-mm^3 volume with details described in [10].

Acoustic response measurements are performed using a broadband speaker and standard reference microphone (1/4 inch LD) for calibration and normalization. A low frequency portion of a response test is presented in Fig 8b, with this particular device characterized by an 80 Hz lower limiting frequency (3dB roll-off). We are currently performing detailed self-noise evaluation of many device types presented here. In addition, realizing multi-microphone configurations is also under development for carrying out sound intensity and other advanced measurements.

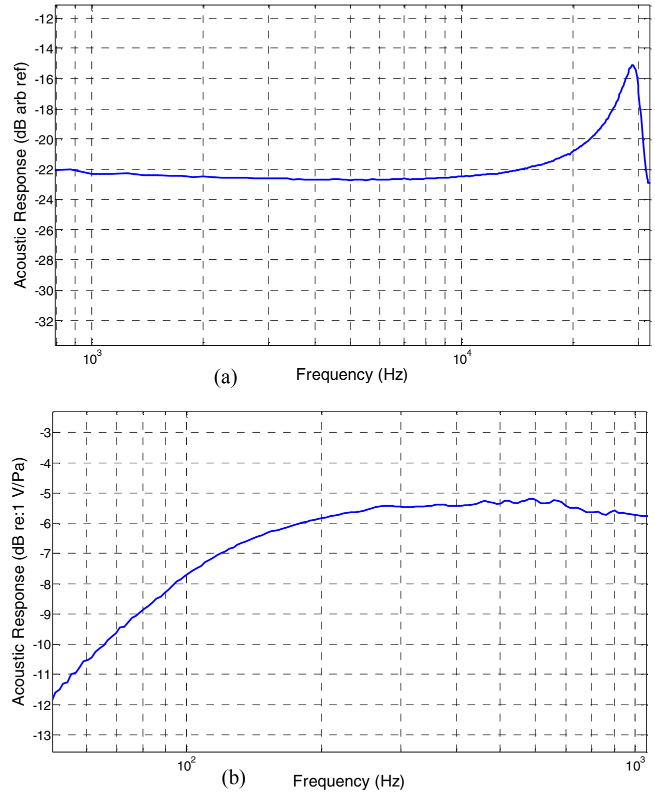

Fig. 8. a) Measured electrostatic frequency response of the 1.2 mm diameter structure shown in Fig 4 showing a 30 kHz diaphragm resonance and b) Low frequency acoustic response data of the same device as measured in the anechoic testing facilities at Georgia Tech. This particular device has a 3 dB low frequency cut-off near 80 Hz.

ACKNOWLEDGMENTS

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REFERENCES

[1] T. B. Gabrielson, "Mechanical-thermal noise in micromachined acoustic and vibration sensors," *IEEE Transactions on Electron Devices,* vol. 40, pp. 903-909, 1993

[2] P. R. Scheeper, B. Nordstrand, J. O. Gullov, B. Liu, T. Clausen, L. Midjord, and T. Storgaard-Larsen, "A new measurement microphone based on MEMS technology," *Microelectromechanical Systems, Journal of,* vol. 12, pp. 880-891, December 2003

[3] N. A. Hall, B. Bicen, M. K. Jeelani, W. Lee, S. Qureshi, M. Okandan, and F. L. Degertekin, "Micromachined microphones with diffraction based optical displacement detection " *Journal of the Acoustical Society of America,* vol. 118, pp. 3000-3009, November 2005

[4] N. A. Hall, W. Lee, and F. L. Degertekin, "Capacitive micromachined ultrasonic transducers with diffraction-based integrated optical displacement detection," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 50, pp. 1570-1580, November 2003

[5] W. Lee, N. A. Hall, Z. Zhou, and F. L. Degertekin, "Fabrication and characterization of a micromachined acoustic sensor with integrated optical readout," *IEEE Journal on Selected Topics in Quantum Electronics,* vol. 10, pp. 643-651, May/June 2004

[6] N. A. Hall, R. Littrell, M. Okandan, B. Bicen, and F. L. Degertekin, "Micromachined optical microphones with low thermal-mechanical noise levels," *Journal of the Acoustical Society of America,* vol. Accepted for publication in July 2007

[7] D. S. Greywall, "Micromachined optical-interference microphone," *Sensors and Actuators A-Physical,* pp. 257-268, 1999

[8] S. C. Thompson, J. L. LoPresti, E. M. Ring, H. G. Nepomuceno, J. J. Beard, W. J. Ballad, and E. V. Carlson, "Noise in miniature microphones," *Journal of the Acoustical Society of America,* vol. 111, pp. 861-866, February 2002

[9] C. Garcia, B. Bicen, N. A. Hall, S. Qureshi, K. Jeelani, and F. L. Degertekin, "An integrated optical microphone test-bed for acoustic measurements," in *Acoustical Society of America*, Salt Lake City, Utah, 2007

[10] N. A. Hall, M. Okandan, R. Littrell, D. Serkland, G. Keeler, K. Peterson, B. Bicen, C. Garcia, and F. L. Degertekin, "Micromachined accelerometers with optical interferometric read-out and integrated electrostatic actuation," *Journal of Microelectromechanical Systems,* vol. In review, 2007

[11] N. A. Hall, R. Littrell, M. Okandan, B. Bicen, and F. L. Degertekin, "Micromachined optical microphones with low thermal-mechanical noise levels," *Journal of the Acoustical Society of America,* vol. In review, 2006