OPTICAL SENSING IN A DIRECTIONAL MEMS MICROPHONE INSPIRED BY THE EARS OF THE PARASITOID FLY, *ORMIA OCHRACEA*

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ABSTRACT

The fabrication and characterization of a biomimetic MEMS directional microphone with integrated optical readout is presented. The use of diffraction-based optical interferometric detection with this novel microphone diaphragm avoids key limitations imposed by capacitive sensing, which is commonly used in miniature microphones. In this study, a biologically-inspired microphone with inter-digitated fingers is fabricated on a silicon substrate using a combination of surface and bulk micromachining techniques. The 1mm×2mm microphone diaphragm is made of polysilicon and has stiffeners and carefully designed hinge supports to ensure that it responds like a rigid body on flexible hinges. The diaphragm is designed to respond to pressure gradients, giving it a first-order directional response to incident sound. This mechanical structure is integrated with a compact optoelectronic readout system. The directivity measurements show the expected figure-8 directivity pattern with a 21dB difference between the maximum and minimum at the first diaphragm resonance frequency of 2 kHz. This concept has the potential of allowing the fabrication of low noise, directional miniature microphones with high sensitivity for hearing aid applications.

1. INTRODUCTION

Conventional microphones often consist of a thin diaphragm along with a backplate electrode positioned in parallel at a small distance away. This permits the detection of the motion of the diaphragm through the capacitance change between the diaphragm and the backplate. There are a few limitations of this configuration. First, the viscous damping caused by the air between the diaphragm and the backplate can have a significant negative impact on the response. Secondly, the signal to noise ratio is negatively influenced by the electronic noise associated with the capacitive sensing and the thermal noise associated with the passive damping. Thirdly, while the electrical sensitivity is proportional to the bias voltage, if the voltage exceeds a critical value the attractive force will cause the diaphragm to collapse against the backplate.

In our microphone design, a directional microphone diaphragm inspired by the ears of the parasitoid fly, *Ormia Ochracea* [1,2,3], is combined with an optical sensing scheme to provide electronic readout of the diaphragm deflection with a minimum of thermal noise.

The optical detection method is based on a phase-sensitive grating structure, where the intensity of reflected diffraction orders is monitored as the displacement signal [4,5,6]. Using vertical cavity surface emitting lasers (VCSELs) as the light source and integrating photodetection electronics as shown in Fig. 1, the overall volume of the interferometer can be reduced to the mm^3 level [7]. The phase sensitive optical grating can be built into the diaphragm (Fig. 1) or can be realized through interdigitated fingers at the ends of the diaphragm as implemented in this study. It has been shown that this method provides near shot noise level displacement noise. Pulsed VCSELs have been used for low-power operation. Low noise and low power are essential characteristics for hearing aid microphones [7].

2. DESIGN AND FABRICATION

The novel biomimetic differential microphone diaphragm shown in Fig. 1 is based on a mechanical model of the ears of the parasitoid fly, *Ormia Ochracea* [2,3]. The 1mm by 2mm diaphragm is constructed of PECVD (plasma-enhanced chemical vapor deposition) polysilicon. It is supported at only two pivot points at the middle and reinforced with stiffening ribs, which greatly increase the stiffness-to-mass ratio. The thickness of the diaphragm is 2 µm. Inter-digitated fingers, which consist of 100 µm long 1µm wide fingers with 4 µm periodicity, are incorporated at the two ends of the diaphragm, the locations with

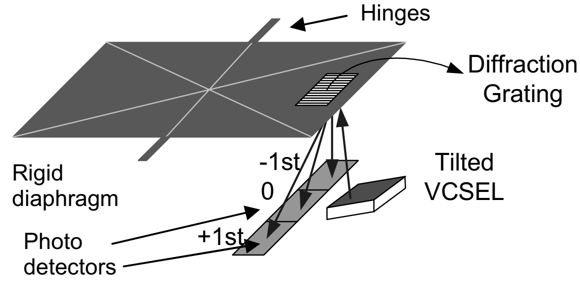

Figure 1. Schematic of a micromachined directional microphone with integrated optical readout.

maximum deflection. The dimensions of this structure have been determined by a detailed finite element-based optimization. This structure provides a highly compliant differential microphone that responds to the differences in pressure on the two sides of the diaphragm that are separated by the hinges at the center.

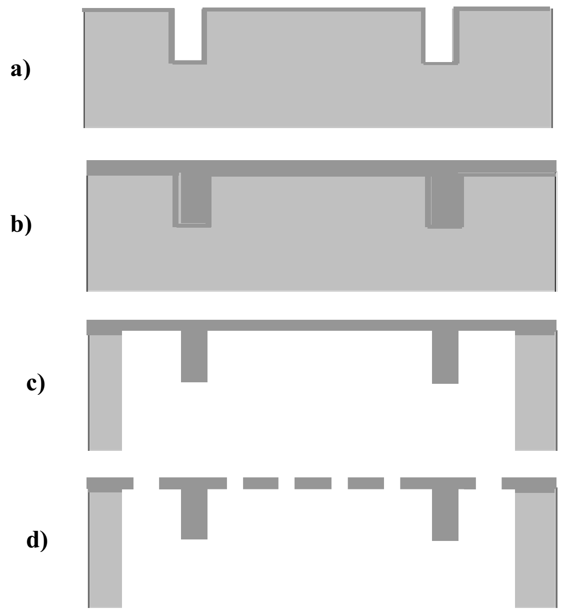

Figure 2. Fabrication process flow for the differential microphone diaphragm with inter-digited fingers at the ends. a) Deep RIE and thermal oxide growth. b) Polysilicon deposition and chemical mechanical polish. c) Backside RIE and thermal oxide removal. d) Polysilicon RIE for fingers and slits.

Micromachining technology is used to fabricate this device. This fabrication technique uses deep-trench etching and sidewall deposition to create very lightweight, very stiff membranes with stiffening ribs at optimal locations. Fig. 2 shows the fabrication process flow for the microphone diaphragm. The fabrication starts with a deep reactive ion trench etch into the 4-inch test grade silicon wafer that acts as the mold for the polysilicon stiffeners. This is followed by a wet oxidation at 1100 ^{o}C to grow a one-micron thick thermal oxide layer on the wafer surface and in the trenches (Fig. 2 a)). This oxide is used as an etch stop for a subsequent backside cavity etch. The next step is to deposit and planerize polysilicon to form a flat diaphragm surface having stiffeners (Fig. 2 b)). The phosphorus-doped polysilicon is deposited at 580 ^{o}C and subsequently annealed at 1100 ^{o}C in argon gas for 60 minutes in order to reduce intrinsic stress in the film. The back cavity is then etched using a deep reactive ion etch and the thermal oxide layer is removed in buffered oxide etchant (Fig. 2 c)). The final step is to etch the polysilicon to define the inter-digited fingers and slits that separate the diaphragm from the substrate (Fig. 2 d)).

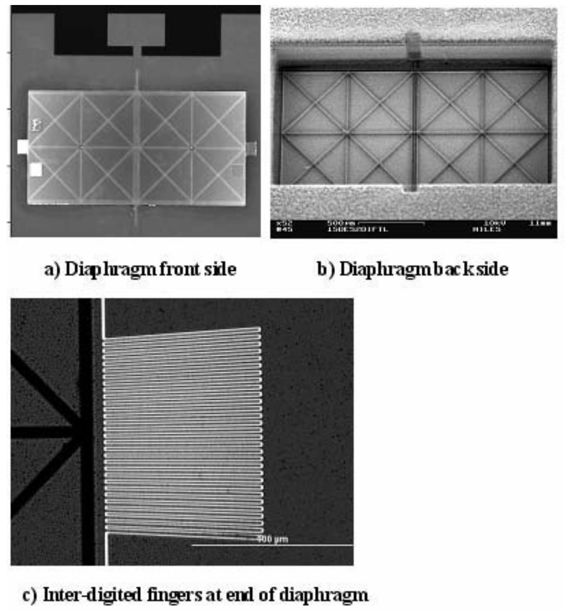

Figure 3. Fabricated differential microphone diaphragm with inter-digited fingers a) Front side optical view. b) Backside view using an SEM. c) Inter-digitated fingers at the end of the diaphragm with backside illumination.

Fig. 3 a) shows the optical image of the front side illuminated with both reflected and transmitted light. The stiffeners are seen as lighter lines and the interdigitated fingers on each end of the diaphragm extend out into the polysilicon layer connected to the silicon substrate. The microphone diaphragm is separated from the substrate with a 2 µm gap around the edge and the center hinges for acoustical damping and electrical isolation. The scanning electron micrograph (SEM) of the backside of the structure shown in Fig. 3-b shows the 3-D nature of the device with the backside cavity and the stiffeners. The details of the inter-digitated fingers can be seen in Fig. 3-c. Illumination with transmitted light in Fig. 3-c shows the stiffeners on the diaphragm as dark lines on the left, whereas the stationary fingers extend out from the polysilicon layer attached to the substrate on the right.

3. DEVICE CHARACTERIZATION

To characterize the response of the biomimetic directional microphone structure, the device is integrated with a hand-held optical detection setup [8]. As shown schematically in Fig. 4, the setup uses a laser diode (λ = 640nm), which is focused down to about a 20 µm diameter spot on the grating. A silicon photodiode array is used to capture the 0^{th} and $\pm1^{st}$ diffraction orders, and transimpedance amplifiers are used for photocurrent to voltage conversion. Furthermore, one can also use electrostatic actuation for sensitivity optimization. Using electrostatic actuation, the device motion is first analyzed under a white light interferometer to determine if it has the proper rocking mode of vibration in which the diaphragm pivots about the hinge axis. The frequency response of the device is then measured indicating a rocking mode resonance at 2 kHz as expected from the design model. This rocking mode is suitable for differential pressure measurement resulting in directional response.

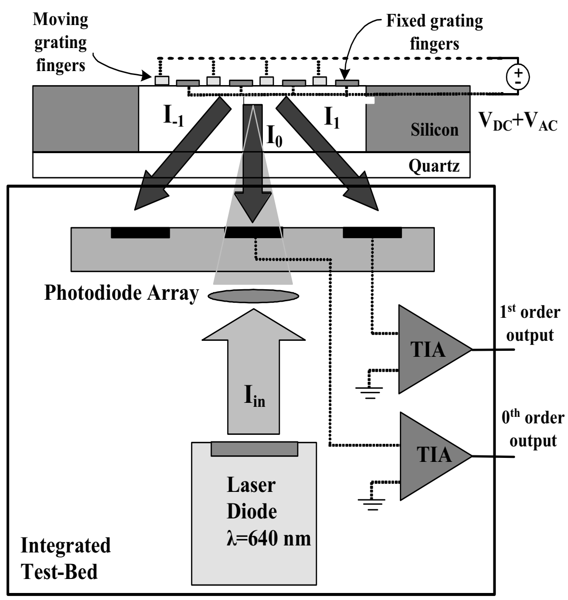

Figure 4. The schematic of the setup integrating the directional microphone diaphragm with optical sensing circuitry. This hand-held setup (10cm×10cm×25cm) is used for both dynamic characterization using electrostatic actuation and also acoustic characterization in anechoic chamber.

To measure the directional response of the microphone the optical detection setup is mounted on a computer controlled rotation stage and placed in an anechoic chamber. A loudspeaker is placed approximately 1m away from the device and driven by a 50-cycle tone burst sine wave at 2 kHz. The top polar plot in Fig. 5 shows the variation of the optical detector output signal as a function of rotation angle φ, i.e. out of plane rotation around an axis perpendicular to the hinge. The data shows only 0.15 dB variation indicating a nearly ideal omnidirectional response. In contrast, when the microphone is rotated in the θ direction, i.e. in-plane rotation around an axis vertical to the microphone diaphragm, the response of the microphone has nearly an ideal Figure-8 pattern with 21.9dB difference between the maxima and minima (Fig. 5 bottom polar plot). The minima correspond to the angles where the wave propagation is along the hinge, resulting in the same pressure applied to the left and right sides. The disturbances and fluctuations of the results shown for incident directions between 150º and 210º come from the shadowing effect of the device packaging. Sound recordings at different angles confirm the highly directional nature of the device.

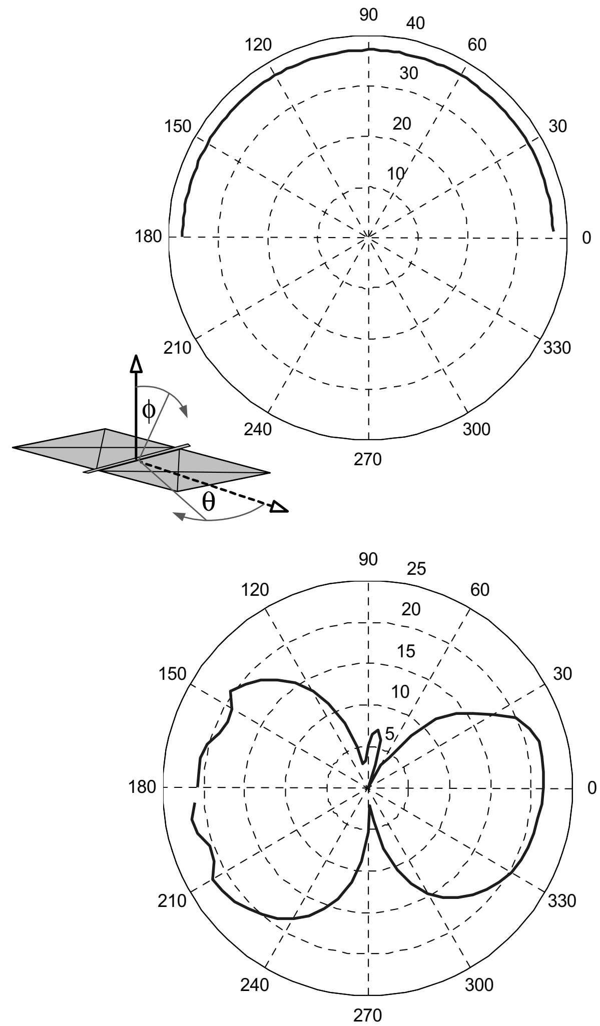

Figure 5. Variation of acoustic response (in dB) of the microphone measured at 2 kHz. Top: Device response in the φ direction showing expected omnidirectional behavior. Bottom: Variation of device response in the θ direction showing expected figure-8 behavior.

These initial results show that this novel biomimetic microphone diaphragm coupled with a diffraction-based optical sensing scheme provides directional response in a miniature MEMS microphone. This type of device should be useful for hearing-aid applications where it is very desirable to reduce external acoustic noise to improve speech intelligibility.

4. CONCLUSION

A micromachined directional microphone has been fabricated and tested that combines a biomimetic differential microphone diaphragm with inter-digitated fingers for optical interferometric detection of the diaphragm motion. The microphone's acoustic response is directional, and has a figure-8 directivity pattern that is typical of a first-order pressure gradient microphone. This miniature directional MEMS microphone has potential for use in hearing aids where it can be extremely beneficial to reduce unwanted sounds.

5. ACKNOWLEDGMENTS

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