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A BIO-INSPIRED MINIATURE COMB SENSE DIFFERENTIAL MICROPHONE DIAPHRAGM

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ABSTRACT

A highly innovative miniature silicon comb sense differential microphone diaphragm is described that is highly stable when subjected to various bias voltages [1]. The bio-inspired microphone diaphragm consists of a 1mm by 2mm stiffener-reinforced plate fabricated out of phosphorous doped polysilicon that is supported on a central hinge [2, 3, and 4]. Interdigitated comb fingers are formed around the perimeter at the ends of the diaphragm by reactive ion etching the polysilicon to create the gaps between the two sets of comb fingers. It is demonstrated with a fabricated prototype device that this design avoids many key limitations of capacitive microphones through use of a unique comb-sensing design and approach. It provides the means for design and construction of highly innovative capacitive microphones with enhanced sensitivity that can be readily and cost-effectively produced through silicon microfabrication. Potential applications include manufacturing of next-generation hearing aids, security devices, portable digital devices, cell phones and teleconferencing equipment.

Keywords : Comb sense, differential microphone, bio-inspired, interdigitated fingers

1. INTRODUCTION

Conventional capacitive microphones often consist of a thin diaphragm with a backplate electrode positioned in parallel at a small distance away. The motion of the diaphragm is detected through the capacitance change between the diaphragm and the backplate. A few known limitations of this configuration include the viscous squeeze-film damping caused by the air between the diaphragm and the backplate, the electronic noise associated with the capacitive sensing, the thermal noise associated with the passive damping, and the critical collapse voltage which limits the electrical sensitivity. All of the above limitations impose significant negative impact on the sensitivity and signal to noise ratio.

Another capacitive sensing scheme is to employ interdigitated comb fingers. Interdigitated comb fingers have been widely used for actuation, frequency tuning, and pressure and acceleration detection [5-11]. The motion of the system is typically in the plane of the device. When the motion causes the gap between the fingers to change, they typically suffer from electromechanical instability which limits the maximum useable voltage [12-15]. When the motion is normal to the plane of the fingers, this instability does pose the same difficulty. Vertical comb-drives have some advantages but often involve chip bonding and hence are more difficult to fabricate [16 and 17].

In this study, a directional microphone diaphragm inspired by the ears of the parasitoid fly, Ormia Ochracea [18,19,20], is combined with interdigitated comb fingers to provide capacitive sensing of the diaphragm deflection without the use of a parallel backplate. The dominant resonant frequency of the diaphragm is designed to be approximately 2 kHz. Interdigitated comb fingers are

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formed around the perimeter of the diaphragm by reactive ion etching the polysilicon to create the gaps between the two sets of comb fingers. The capacitance between the diaphragm fingers and the fixed fingers varies when the diaphragm responds to varying sound pressure gradient, which can be detected using traditional capacitive sensing schemes. Because the fingers may be formed with great stiffness and the relative motion of the fingers is normal to the microphone diaphragm plane, this design effectively avoids the classic problem in typical capacitive microphones of attraction of the diaphragm to the back plate, allowing the application of higher bias voltages. Because the effective stiffness due to the bias voltage stiffens the diaphragm rather than softens it, as occurs in parallel plate capacitive sensors, high bias voltages do not result in the collapse instability that is often a concern in parallel plate capacitive sensors.

2. DESIGN AND FABRICATION

The novel biomimetic silicon differential microphone diaphragm is based on a mechanical model of the ears of the parasitoid fly, Ormia Ochracea [1-3, 19]. The dimensions of this structure have been determined by a detailed finite element-based optimization. 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. Both the diaphragm and stiffening rids are made of LPCVD (low pressure chemical vapor deposition) polysilicon. The diaphragm is ~2 µm thick and the stiffening ribs are 4 µm wide and 40 µm tall. 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 [4, 20-22]. Interdigitated fingers, which consist of 100 µm long, 1.5 µm wide fingers with 6 µm periodicity, are incorporated at the perimeter of the two ends of the diaphragm, the locations with maximum deflection. Fig. 1 shows the L-Edit image for the microphone diaphragm with interdigitated comb sense fingers.

The biologically-inspired microphone with interdigitated comb sense fingers is fabricated on a silicon substrate using a combination of surface and bulk micromachining techniques. 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 (Fig. 2 1)). This is followed by a wet oxidation at 1100 degrees Celsius to grow a one-micron thick thermal oxide layer on the wafer surface and in the trenches (Fig. 2 2)). This oxide is used as an etch stop for a subsequent backside cavity etch. The phosphorus-doped polysilicon is then deposited at 580 degrees Celsius and subsequently annealed at 1100 degrees Celsius in argon gas for 60 minutes in order to reduce intrinsic stress in the film (Fig. 2 3)). The next step is to planerize the annealed polysilicon to form a flat diaphragm surface having stiffeners followed by reactive ion etching to define the interdigitated comb sense fingers and slits that separate the diaphragm from the substrate (Fig. 2 4)). The back cavity is then etched using a deep reactive ion etch (Fig. 2 5)) and finally the thermal oxide layer is removed in buffered oxide etchant to fully release the microphone diaphragm with comb sense fingers (Fig. 2 6)) [3, 4, 21 and 22].

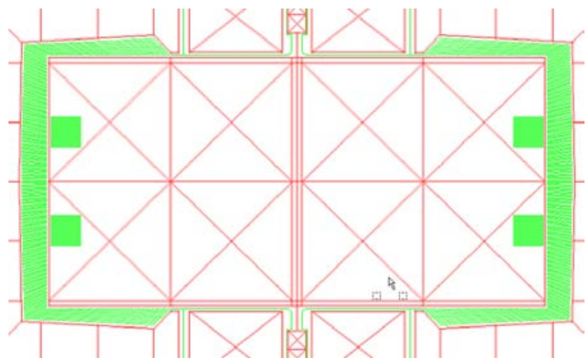

Fig. 1 L-Edit image of the silicon differential microphone diaphragm with comb fingers, the light green lines are the slits that define the diaphragm and the comb fingers, the red lines are the stiffeners that reinforce the diaphragm

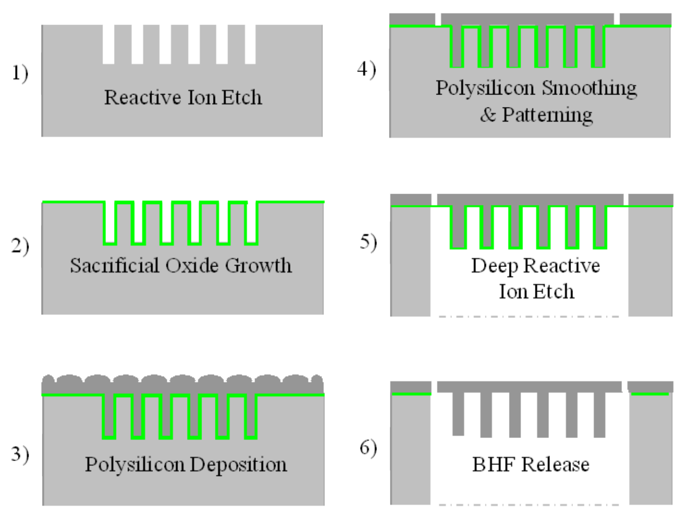

Fig. 2 Fabrication process flow for the silicon differential microphone diaphragm with interdigitated comb fingers at

the perimeter of the diaphragm. 1) Deep RIE. 2) Thermal oxide growth. 3) Polysilicon deposition. 4) Polysilicon smoothing and RIE to define diaphragm and comb fingers. 5) Backside RIE. 6) Buffered hydrofluoric acid etching to remove the thermal oxide.

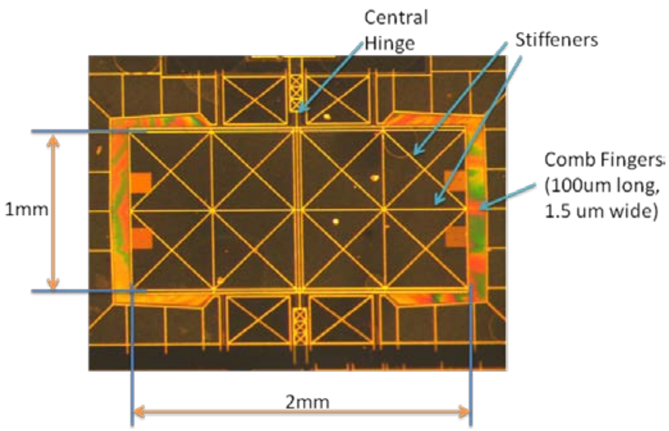

Fig. 3 Microscope image of the fabricated silicon differential microphone diaphragm with comb fingers

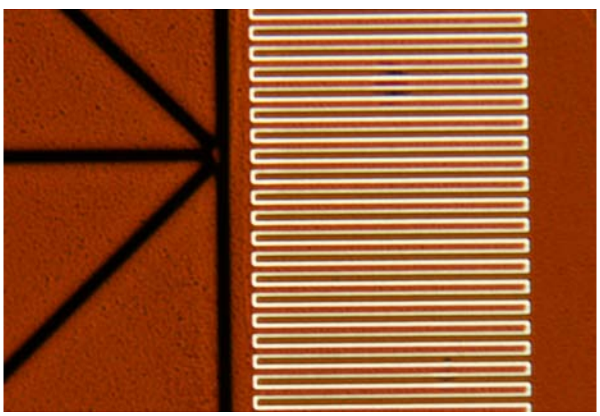

Fig. 4 Close-up microscope image of the two sets of comb fingers (diaphragm is on the left)

Fig. 3 shows the optical image of the front side of the silicon microphone diaphragm 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. The close-up details of the interdigitated fingers can be seen in Fig. 4. Illumination with transmitted light in Fig. 4 shows the stiffeners on the diaphragm as dark lines on the left, whereas the 2 μm slits that separate the two sets of comb sense fingers as white lines. The moving comb sense fingers extend out from the polysilicon layer on the diaphragm and the stationary fingers are attached to the substrate on the right.

3. DEVICE CHARACTERIZATION

The acoustic response of this novel micro-fabricated microphone diaphragm is measured with the setup pictured in Fig. 5. The experimental setup includes a loudspeaker, a reference microphone, a laser vibrometer, and a data acquisition system. A circular printed circuit board with the microphone chip and capacitive sensing circuit is attached to a motorized rotation stage which allows the orientation of the microphone diaphragm to be changed relative to the loudspeaker for measuring directivity. The laser vibrometer is used to verify the mechanical response of the microphone diaphragm.

A broad bandwidth continuous random signal is used to drive the loudspeaker. The reference microphone is positioned to measure the sound pressure near the microphone diaphragm as shown in Fig. 5. Acoustic frequency response functions for the mechanical deflection of the diaphragm and electrical output of the circuit are obtained with respect to the sound pressure measured with the reference microphone.

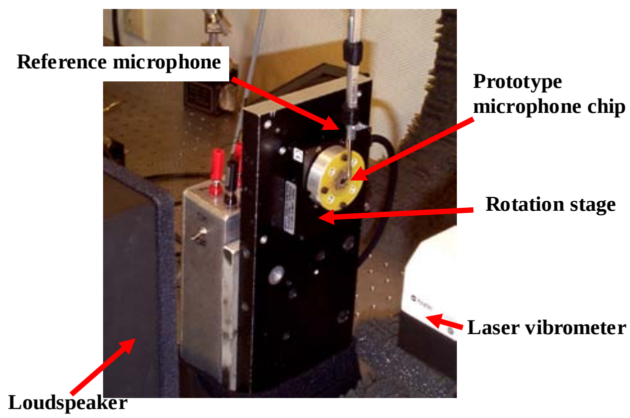

Fig. 5 Test setup used to measure the acoustic response of the microphone diaphragm

The mechanical acoustic frequency response was obtained with the laser vibrometer indicating a rocking mode resonance for the device around 2 kHz, as expected from the design model. Measurements were also obtained with various bias voltages applied across the diaphragm fingers. Shown in Fig. 6 are the mechanical acoustic responses measured with the sound incidence direction corresponding to the maximum diaphragm response for three different levels of DC bias applied to the fixed fingers. The data show that the resonant frequency is roughly proportional to the bias voltage.

The forces due to the bias voltage on the fingers produce a positive, linear spring for small deflections and hence, the bias voltage will not cause any instability in the mechanical system. This is in contrast with the very well-known difficulty in conventional capacitive microphones that use backplates to sense capacitance changes. The parallel plate capacitor formed by the diaphragm and backplate is prone to severe instability and collapse when large bias voltages or flexible diaphragms are used. Our use of comb fingers completely avoids this difficulty.

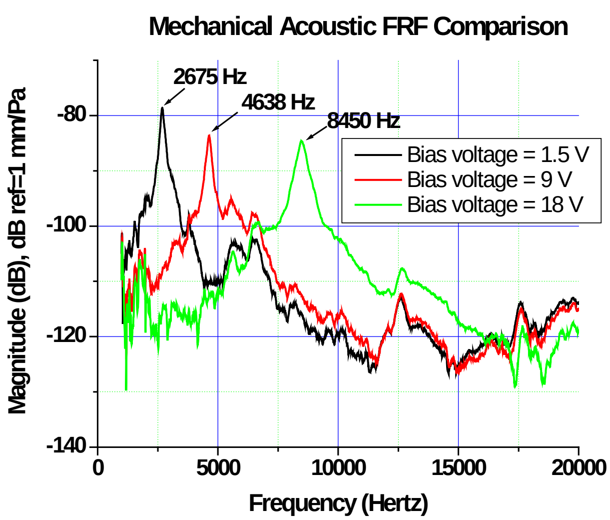

Fig. 6: Mechanical acoustic frequency response functions obtained from the laser vibrometer for various bias voltages. The sound incidence for the measurements corresponds to maximum response direction. The resonant frequency of the diaphragm is roughly proportional to the bias voltage resulting in higher mechanical stability with higher bias voltages.

The electrical output of the capacitive sensing circuit was also measured. Fig. 7 shows a comparison of the circuit output with the mechanical deflection obtained with the laser vibrometer. These data show that the circuit output corresponds well to the diaphragm motion.

The maximum response occurs when the wave propagation is along the long axis of the microphone diaphragm. 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. Directivity measurements were performed to verify this by measuring the electrical circuit output while varying the orientation of the microphone diaphragm with the rotation stage. These measurements show the expected figure-8 directivity pattern as seen in Fig. 8. Plotted in red is data obtained from the capacitive sensing circuit, normalized to the maximum response value. This very closely matches the ideal figure-8 pattern plotted in black.

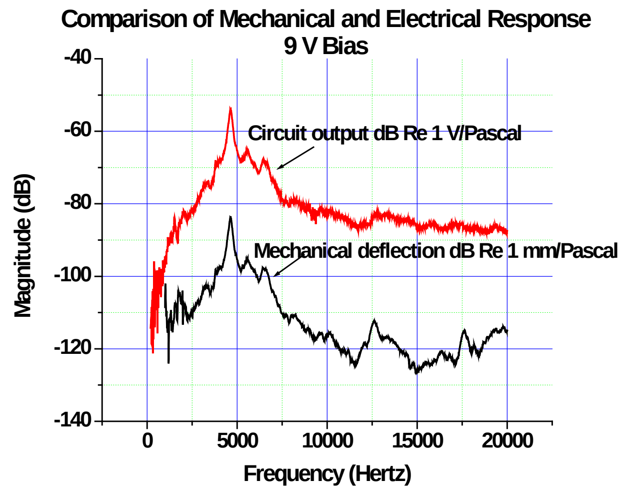

Fig. 7: Comparison of the electrical output and mechanical acoustic response of the diaphragm. The circuit output closely corresponds to the diaphragm motion.

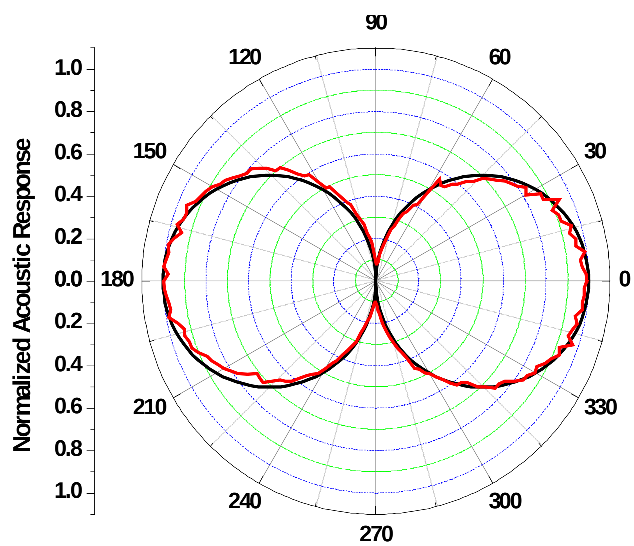

Fig. 8: Measured directivity pattern obtained from circuit output. The measurement (red) is very close to the ideal figure “8” pattern (black).

These initial results show that this novel biomimetic microphone diaphragm coupled with interdigitated comb finger sensing scheme provides directional response in a miniature MEMS microphone.

4. CONCLUSION

A micromachined bio-inspired miniature comb sense directional microphone has been fabricated and acousticaly tested that combines a biomimetic differential microphone diaphragm with inter-digitated comb sense fingers for capacitive 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.

It is demonstrated that this design avoids many shortcomings and limitations of conventional capacitive microphones by combining a highly innovative differential microphone diaphragm with a unique comb-sensing design and approach. This provides the means for design and construction of highly innovative capacitive microphones that allow higher bias voltage, higher output voltage relative to conventional parallel plate microphones. It is shown that this device can be readily and cost-effectively produced through silicon microfabrication.

5. ACKNOWLEDGMENTS

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