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Microfabrication of coupled fluid–structure systems with applications in acoustic sensing

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Abstract

A fabrication process for manufacturing coupled fluid–structure microsystems is described. This process allows production of a novel class of trapped-fluid acoustic sensors. The systems consist of wafer-thick fluid chambers bounded by arbitrarily shaped membranes. A stacked film structure of silicon nitride and boron doped polysilicon is used to reduce residual stresses in the membranes. Tin–gold fluxless solder bonding is used to fabricate capacitive structures which allow electrical sensing of membrane vibrations. An acoustic sensor fabricated using this process is demonstrated. An equivalent acoustic circuit model for the system is described, and models the low-frequency system response accurately. Experimental measurements of sensitivity, noise density, and linearity are presented.

Keywords: MEMS; Microphone; Acoustic; Sensor; Microfabrication

1. Introduction

A fabrication process and mathematical modeling framework has been developed for the production of trapped-fluid microsensors. These structural-acoustic systems consist of a wafer-thick fluid chamber coupled to multiple arbitrarily shaped membranes. A two stage backside deep reactive ion etching (DRIE) process is used to produce the fluid chamber, and to define the shape of the membranes. The membranes themselves are silicon nitride/p++ polysilicon/silicon nitride laminates which have a low net tensile stress, are electrically conducting, and yet are electrically isolated both from the environment and the trapped fluid. Sn–Au fluxless solder bonding is used to attach a top Pyrex glass cover which incorporates a Cr/Pt top electrode. This results in a structure which is capacitively coupled to the membranes and can be used for sensing or actuation. As the small capacitive gap is defined by a dry bonding step at the end of the process, there are no problems with in-process stiction, a problem which is often associated with large area membranes and narrow sense gaps.

Development of the fabrication process was motivated by the authors' ongoing efforts to produce lifesize micromachined cochlear models and biomimetic cochlear-like sensors [1–3]. In order to accomplish this task, a fabrication process was required to produce a deep (wafer thick), fluid-filled chamber coupled to an exponentially tapered membrane. In addition, multiple sensing structures needed to be integrated into the structure to measure vibration of the membrane in response to traveling fluid–structure waves. For additional details on hydromechanical cochlear models, see work by the authors [1–3] and other researchers [4–7].

In this paper, we report a trapped-fluid acoustic structure with a single sensing channel. This structure is not cochlear-like, as it does not have a long, tapered membrane with variable compliance. Nor does it have multiple sensing channels. Rather, the sensor system was built to demonstrate the feasibility of the new fabrication process at producing a trapped-fluid microstructure with integrated capacitive sensing.

To our knowledge, there is no example of other trapped-fluid micromachined acoustic sensors in the literature. However, single channel micromachined capacitively sensed microphones have been designed and constructed by a number of researchers [8–11]. The sensor that we have produced differs from the traditional design by sealing the backing cavity and filling it with a

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liquid, in this case silicone oil, rather than air. This has two primary effects. First, it increases the dynamic mass of the sensor. This reduces the frequency of the primary resonance, thereby reducing bandwidth. In addition, since more of the dynamic mass comes from the trapped fluid, the mass loading from the environment has less effect on the sensor dynamics, reducing sensitivity to the density of the environment. Secondly, as in the cochlea, the fluid serves as an acoustic transmission medium, allowing the acoustic input to be located at a physically remote location from the location at which measurements occur.

In addition, fabrication of the backing cavity in many of these earlier devices was accomplished using anisotropic liquid-phase etching of silicon by potassium hydroxide solutions (KOH). Due to the cubic symmetry of the single crystal silicon structure, use of an anisotropic etchant such as KOH restricted the membrane to a rectangular shape. In addition, the shape of the backing cavity that was formed behind the membrane was completely determined by the shape of the membrane. The fabrication process described here is not constrained in these ways.

Following a description of the fabrication process, a mathematical model of the system is presented. The model captures the low frequency physics in a very efficient manner. Pretension in the membrane, fluid loading from the trapped fluid, and squeeze film damping in the air gap are included in the model. Model predictions are compared to experimental measurements of the system frequency response with good agreement at low frequencies (below 2 kHz).

2. Design

Before proceeding to a description of the fabrication process, a brief description of the system design is given to aid in visualization. The mechanical portion of the sensor, diagrammed in Fig. 1, is a square silicon die 1.25 cm on a side. It consists of a 0.52 mm deep, 10 mm diameter fluid chamber, filled with silicone oil of 200 cSt viscosity. This chamber is constrained on one side by a series of flexible membranes. The center membrane is circular with a 2.5 mm diameter. Arrayed around the outer portions of the chamber are two rings of eight arc segments, each subtending 30°, with inner and outer diameters as shown in the figure. The bottom side of the chamber is sealed by a square Pyrex die 1.25 cm on a side. On the top side, a smaller square Pyrex glass die, 5 mm on a side, is bonded over the center of the silicon chip. A thin film Cr/Pt electrode on the bottom side of the Pyrex forms a parallel plate capacitor with the central circular membrane.

Incoming sound excites motion of the outer "input" membranes, generating an acoustic pressure in the fluid chamber. This causes deflection of the center "sensing" membrane. With a dc bias applied between the Cr/Pt electrode and the "sensing"

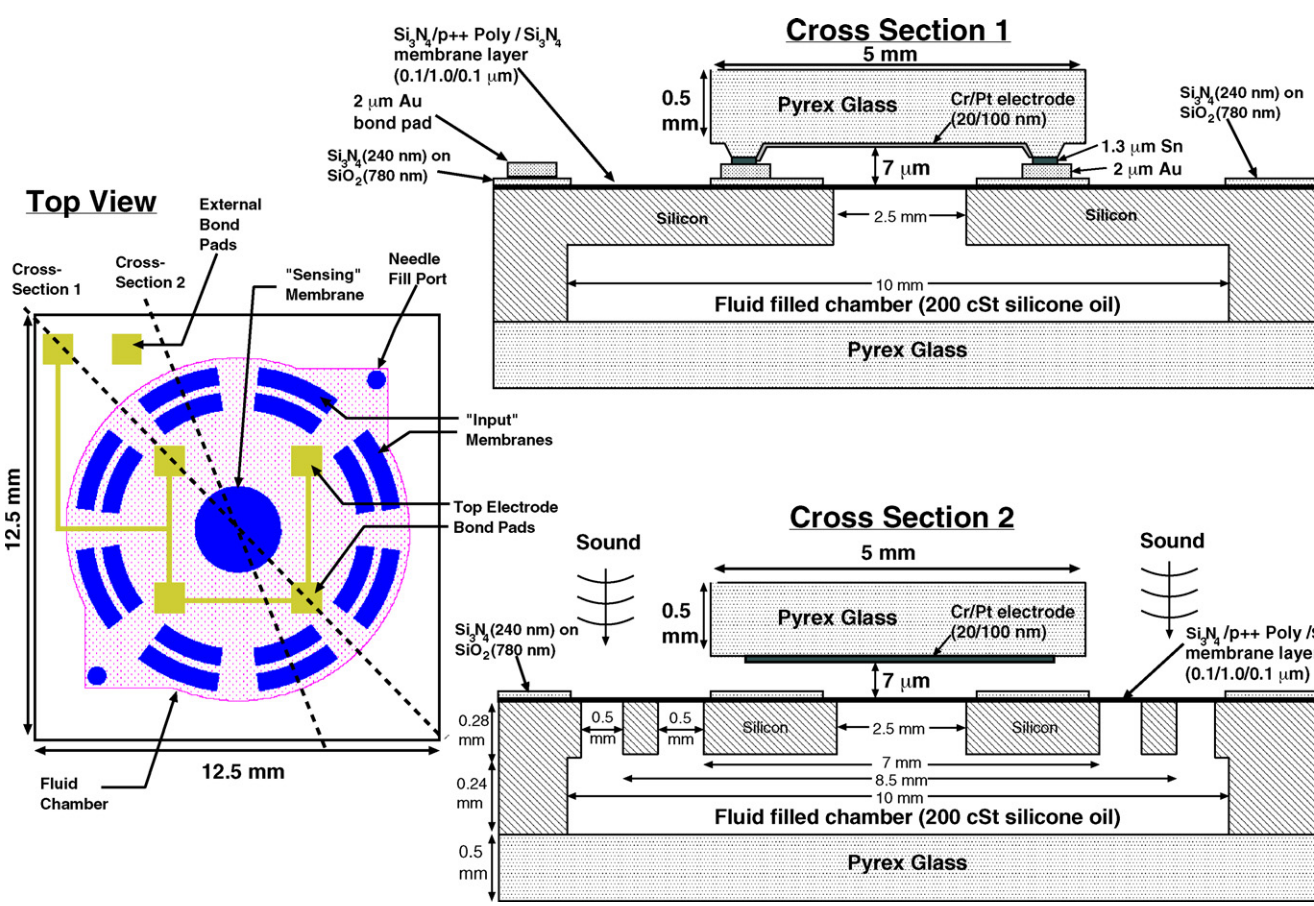

Fig. 1. Conceptual diagram of the sensor system. The top view (on the left) shows the layout of the metallization, the location of the flexible membranes, and the location of the bonding pads. Two cross-sections (on the right) show the geometry of the fluid chamber and the thickness of the various thin films.