Research of the mechanical parameters of silicon membranes for acoustic sensors

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Abstract. This paper presents the results of modeling and fabrication of silicon membranes for acoustic sensors with resonant frequency from 2 kHz to 60 kHz and pressures from 0.1 to 14 Pa. An analysis of the constructive and mechanical parameters of monocrystalline silicon membranes is performed. The range of membrane edge length (6-20 mm) at a fixed thickness of 50 μm determined. The etching process of a silicon wafer by anisotropic wet etching was studied. A process flow for manufacturing silicon membranes is proposed. The results of experimental studies of amplitude-frequency characteristic of membranes are obtained.

1. Introduction
Micromechanical acoustic sensors suitable as an alternative to standard ones due to such advantages as wide bandwidth, flexible geometry, impedance matching between the transducer and the environment [1-3]. The sonar monitoring application area of the acoustic sensor is defined by such parameters as the amplitude-frequency response and the minimum detectable acoustic pressure [4]. In [5] an adaptive fiber-optic hydrophone with optical fiber sensor as a sensitive element was proposed. The sensitivity of that hydrophone varies from 0.1 to 14 Pa in the frequency range from 2 kHz to 60 kHz. Adaptation of the sensors to different applications is provided by variety of materials, shape and size of the membrane [6,7]. For most practical tasks it is necessary to optimize the geometrical and mechanical parameters of the membrane so that the resulting structure satisfies the aforementioned ranges of pressure and resonance frequency.

The purpose of this work is to study the structural and mechanical parameters of silicon membranes of the acoustic wave sensors based on fiber-optic adaptive interferometer.

2. Experimental details
In this paper we study the using of a primary membrane-type acoustic pressure sensor. Due to technical limitations of the fabrication method a silicon membrane with square shape and thickness of 50 μm is chosen (figure 1). This membrane thickness provides acceptable mechanical strength and surface quality.
of membrane. In modeling by the finite element method the length of the membrane edge ($a$) is varied within 6-20 mm. The geometric parameters of the membrane are chosen taking into account the values of pressure (0.1-14 Pa), resonant frequency (2-60 kHz) and the dynamic range of the interferometer, which allows measuring the membrane deflection in range of 2-130 nm.

![Figure 1. Displacement (nm) of the membrane under load.](image)

Double side polished 100-mm monocrystalline silicon (100) wafers with a thickness of 320 μm were used for the membranes fabrication. Silicon oxide films obtained by thermal oxidation with a thickness of 600 nm were used as a masking coating [8]. Instead of thermal oxide, a plasma oxide of a larger thickness can be used [9,10]. A pattern in the silicon oxide film was formed on the wafer backside by the contact photolithography and isotropic wet etching [11]. Then by anisotropic wet etching in 30% KOH solution at temperature of 70-75°C silicon membranes with thickness of 50±20 μm were formed. Finally, the protective layers were removed in a 10% HF solution.

Membrane vibrations were measured by the fiber-optic adaptive holographic interferometer [12]. Membranes were fixed on a rigid base. The laser radiation of the interferometer was brought to the membrane by multimode optical fiber. The distance between the fibre output and the membrane was 0.2-0.5 mm. Adaptive holographic interferometer based on dynamic holograms formed in a photorefractive crystal was used to stabilise the operating characteristics of a laser acoustic sensor [13,14]. The radiation reflected from the membrane returns back into the fiber and form a signal wave of interferometer. The mechanical vibrations of the membrane caused by the acoustic wave impact lead to the phase modulation of signal wave. The radiation of the signal wave is directed into the photorefractive crystal where due to the photorefractive effect the interaction of waves at the dynamic hologram provides the precise conjugation of wave fronts. Thus the signal wave phase modulation efficiently converse into the variations of intensity recorded by the photodetector. A rigid base with a fixed membrane and optical fiber was lowered into water (the container dimensions are 0.4×0.4×0.3 m). The acoustic field was generated by a piezoceramic transducer BC310 located at distance of 0.2 m from the membrane. Photodetector signal proportional to membrane deflection was recorded by a spectrum analyzer Agilent N9030A and oscilloscope Agilent DSO-X 3012 A.

3. Results and discussions
Based on the finite element model in the software package Comsol Multiphysics values of the first 6 resonant frequencies ($f_n$) were obtained in dependence of the membrane edge length (figure 2).

Figure 2 shows that with the edge length decrease the resonant frequency tends to shift towards higher values.

For membranes fabrication by anisotropic wet etching the process flow was proposed and topology calculations, design and fabrication of a photomask were performed. In accordance with the given route the silicon membranes were formed (figure 3).
Figure 2. Dependence of the first 6 resonant frequencies ($f_n$) on the length of the membrane edge ($a$).

Figure 3. Silicon membrane (8×8 mm, thickness 68 µm).

Figure 4 shows the experimentally measured in water amplitude-frequency characteristics of three membranes with different geometries.

Figure 4. Experimentally measured amplitude-frequency characteristics of three membranes with thickness of 68 µm, 168 µm, 78 µm.
As it's shown in figure 4 the amplitude-frequency dependencies of all membranes have a resonance character. The highest sensitivity of the membrane is 8.2 mrad/Pa at frequency of 17 kHz. Thus the acoustic sensor based on silicone membrane with such sensitivity allows detecting weak signals with an acoustic pressure of 5 MPa.

4. Conclusion
The dependence of the first 6 resonant frequencies on the lengths of the square silicon membranes edge (6-20 mm) is received using the finite element method. Parameters of anisotropic wet etching of silicon wafer were studied. Based on the obtained results square silicon membranes with a thickness of 50±20 µm and edge lengths from 6 to 20 mm were formed. The characteristics of an acoustic sensor based on fabricated silicon membranes were experimentally determined. The amplitude-frequency characteristics were experimentally measured for three membranes of different geometries for acoustic sensor performing in water. The highest sensor sensitivity of 82 mrad/Pa and detection threshold of 5 MPa were achieved using a membrane with a thickness of 68 µm.

The obtained results could be used to optimize the design and fabrication processes of silicon membranes for acoustic sensors.

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