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Optical-acoustic radiation receivers with a freely suspended membrane

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The evolution of the main unit of an optical-acoustic pressure transducer-sensor is considered. A consistent transition from a membrane pressure sensor with rigid fixation of the membrane along the contour, leading to uncontrolled mechanical stresses and changes in the main metrological parameters to cantilever pressure sensors in which only one side is fixed, which leads to an increase in sensitivity by more than 140 times, is shown. It is shown that by chemical etching of four L-shaped narrow through grooves on a membrane foil in one technological cycle, a four-point Z-shaped skew-symmetric suspension can be formed, containing a completely deformation-free central membrane element of a square shape, a four-point angular elastic suspension in the form of four narrow elastic sensor elements located along the lateral sides of the non-deformable membrane element and rigidly fixed to the support contour, and a support contour.

Keywords: sensitive element; membrane; cantilever; sensitivity; elastic suspension.

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Introduction

Membrane pressure transmitters are among the critical structural elements of opto-acoustic radiation detectors and determine metrological characteristics of the device to a significant extent [1, 2]. Operating principle of **membrane pressure transmitters** is based on deformation of the elastic membrane, which responds to changes of external pressure. A capacitive membrane transmitter is capable of measuring a pressure very accurately over a range of 3.5 to 4 orders of magnitude, with the lower limit down to 10^{-5} mbar and accuracy of $\pm (0.15-0.35)$. Readings of a capacitive membrane transmitter do not depend on the type of gas filling the expansion and compensation chambers. Developed by Knowles (Illinois, USA) using the in-house CMOS/MEMS technology platform launched in 2002, SiSonic™ series silicon-based microphones are now in their fourth generation and are sold worldwide in the amounts exceeding 1 billion pieces per year.

Membranes

The sensitivity of an opto-acoustic detector (OAD) is defined as the minimum radiation power at the input that allows for reliable signal extraction at the background level and the converter's inherent noise. It can be calculated as the product of partial sensitivities of photothermal (S_{I-T}), thermoacoustic (S_{T-P}), acoustomechanical ($S_{P-\delta}$), and electromechanical ($S_{\delta-U}$) conversion stages:

$$S_{\text{OAH}} = S_{I-T} S_{T-P} S_{P-\delta} S_{\delta-U} = \frac{\Delta T}{\Delta I} \frac{\Delta P}{\Delta T} \frac{\Delta \delta}{\Delta P} \frac{\Delta U}{\Delta \delta}.$$

Theoretical and experimental studies have shown that the limiting stage in the conversion chain is acoustomechanical stage $S_{P-\delta}$ implemented as a pressure transmitter.

Sensitivity δ (deflection magnitude at the center of a flat membrane rigidly fixed along its contour) for small displacements under pressure P is expressed by formula [3]:

$$\delta = \frac{3(1-\mu^2)PR^4}{16Rh^3},$$

where R is the membrane's working radius (along the fixation contour); h is the membrane thickness; E , μ are the Young's modulus and Poisson's ratio of the membrane material, respectively. In existing OAD designs, membrane deflections at the threshold values of the measured radiation fluxes amount to a few angstroms.

Physico-mechanical properties of membranes depend strongly on the material, structure, surface properties, and technology. It can be derived from the given expression that the membrane transducer sensitivity is determined by the physical properties of the membrane material (E , μ) and design parameters (R , h). Superlinear dependencies of sensitivity on R^4 , h^3 cause the supersensitivity of membrane sensors to changes in device parameters, which is a difficult to handle when designing large-dimensional matrix devices.

Membrane Manufacturing Material

Designs have been evolving by changing sequentially from metallic membranes made of duralumin, silver, nickel, titanium, and titanium alloys VT16 or VT35 with thicknesses of 40-100 nm, to bimorph polymer membranes coated with a reflective silver or antimony layer approximately 100 Å thick [4]. Membrane devices designed using MEMS technologies and widely employed for microminiaturization are usually made of: silicon Si membrane which is formed by etching a substrate down to thicknesses of 2-5 μm; silicon dioxide SiO₂, silicon nitride Si₃N₄, silicon carbide SiC, carbon C, aluminum nitride AlN, boron nitride BN produced both from the gas phase and by ion-chemical deposition methods. Silicon nitride (Si₃N₄) is used as the base material for ultrathin membranes since it is one of the primary materials in microelectronics with a well-established fabrication technology and known properties [5, 6].

Promising materials for creating membranes are kapton and graphene. Kapton is a polyimide film used in various space tools

developed by DuPont in the 1960s. Kapton is an elastic dielectric, which is stable over a wide temperature range from -273 to +400 °C, which allows handling the embrittlement in metal and polymer membranes at low temperatures. It is used for manufacturing flexible printed circuit boards and outer layers of spacesuits [7].

Graphene The known works on designing a new generation of opto-acoustic transducers [8, 9] attribute the choice of single-layer graphene (SLG) for fabricating a flexible membrane to such main factors as the extremely small thickness and extremely high elasticity and mechanical strength of the material, which guaranteed a significant increase of sensitivity. Additionally, the use of single-layer graphene membranes allows not only to achieve the record-breaking sensitivity enhancement but also to almost entirely eliminate such traditional drawbacks of transducers as high susceptibility to acoustic and vibrational noise, while ensuring increased response speed, expanded dynamic range, and ability to operate not only at room temperatures but also under extreme deep cooling.

Numerous experiments on selecting membrane shapes were aimed not at increasing sensitivity, but primarily at obtaining the required frequency response.

The study of the possibilities of enhancing the sensitivity of opto-acoustic transducers with membranes of various geometric shapes (square, circular, and rectangular) rigidly fixed along the perimeter has revealed that the use of a circular membrane provides the maximum change in the sensing element's capacitance under pressure as compared to those of sensing elements with membranes of other geometric shapes [10].

The technological challenges, which have not been fully resolved to date, are related to poor control of mechanical stresses from the rigid fixation of membranes and to the difficult control of the etching thickness of ultrathin (about 1 μm or less) membranes in MEMS technologies, which calls for individual calibration of pressure transducers.

Cantilever

A thin reflective film rigidly fixed on one side in a conventional photoacoustic cell used instead of a classical flexible membrane was first

proposed in the paper by de Paula [11]. An elastic cantilever, as a precision micro-dynamometer with a threshold of 1 piconewton, was first used in an atomic force microscope in 1982.

A cantilever is a thin, elastic U-shaped plate of length α , width b ($b < \alpha$), and thickness h ($h \ll \alpha, b$), which is rigidly fixed along the narrow side b . The geometry of the cantilever determines its stiffness varying over a wide range. The cantilever's stiffness coefficient $K = Ebh^3/4\alpha^3$, where E is the Young's modulus of the cantilever material, b is the width, h is the thickness, and a is the length of the rectangular cantilever. The cantilever's stiffness coefficient, which largely determines the sensitivity of the device, can vary over a very wide range ($10^{-4} \div 10$ N/m).

The main property of a cantilever is its deflection under the action of an applied force. Its main characteristic is its elastic constant. The sensing element of the cantilever-type pressure transmitter of the opto-acoustic detector (OAD) shown in Fig. 1 is structurally different from the cantilevers used in atomic force microscopy [12]. It consists of a substrate that completely covers the acoustic aperture of OAD housing a movable cantilever element separated from the substrate on three sides by a narrow through micro-groove several micrometers wide. A reflective coating (platinum, gold, aluminum) is applied on the cantilever side facing the compensation chamber for the optical readout system.

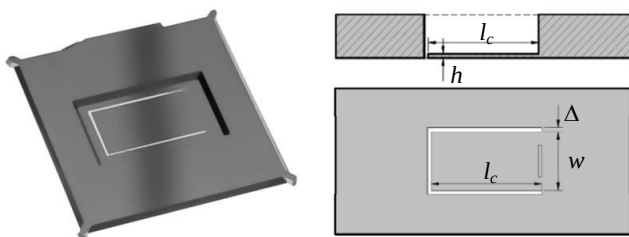


Fig. 1. Photo and schematic diagram of the OAD cantilever as per [13]

The relationship between cantilever's deflection δ and applied stress P is determined by

Stoney's formula: $\delta = \frac{3P(1-\mu)}{E} \left(\frac{L_c}{h} \right)^2$, where E ,

μ are the Young's modulus and Poisson's ratio of the cantilever material, respectively; L_c is the beam length; h is the cantilever beam thickness.

Cantilever's stiffness is defined by expression $k = \frac{Ewh^3}{4L_c^3}$, where w is the cantilever's width.

The maximum deflection of such beam under uniformly distributed load $\delta_{\max} = \frac{PL_c^4}{8EI}$ and

maximum deflection angle $\theta_{\max} = \frac{PL_c^3}{6EI}$ where I is the moment of inertia $I = \frac{wh^3}{12}$. Then

$$\delta_{\max} = \frac{3PL_c^4}{2Ewh^3} \text{ and } \theta_{\max} = \frac{2PL_c^3}{Ewh^3}.$$

$$\text{Cantilever's deflection } \delta_L = \frac{PL^2}{12EI} + \left[2L_c L - 3L_c^2 - \frac{L^2}{2} \right].$$

The theoretical assessment of the sensitivity of a classical rigidly-fixed circular membrane and a rectangular cantilever of equal area showed that the deflection of the cantilever's free end exceeds that of the circular membrane's center by 140.6 times [13]. Experimental studies [14] demonstrated for cells with a simple microphone, a differential microphone, and a cantilever pressure transmitter, with deflections measured using a laser interferometer, that their sensitivity values were 3.1×10^{-7} , 1.7×10^{-7} and $2.2 \times 10^{-9} \text{ cm}^{-1} \cdot \text{W} \cdot \text{Hz}^{1/2}$, respectively, which is in good agreement with the theoretical estimate.

Cantilever's stiffness $k = \frac{Ewh^3}{4L_c^3}$ is typically

2 to 3 orders of magnitude lower than that of the membrane, and displacement of the cantilever's end can reach tens of micrometers without any nonlinear or limiting effects. This significant increase in sensitivity is due to the fundamental difference in the behavior of plates (where bending deformations prevail) as compared to membranes (where tensile deformations prevail) in case of linear and nonlinear deformations.

Currently, the research groups of Stanford University are the leaders in development of cantilever-type micromechanical devices. They have designed cantilevers with a stiffness of 10^{-5} N/m capable of detecting forces as low as 10^{-18} N, and cantilevers with a mechanical

response time of 90 ns [15].

For the purpose of calculation [16], the cantilever is considered a rigidly-fixed beam with structural length L_C , width w , and thickness h loaded by uniformly distributed load P (see Fig. 2).

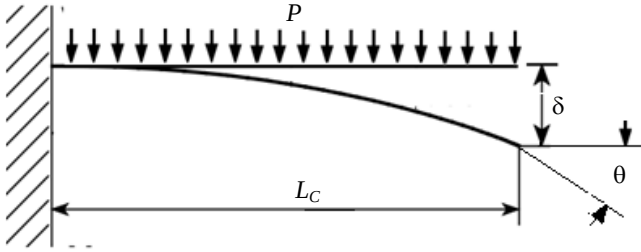


Fig. 2. Calculation diagram for the cantilever beam under uniformly distributed load

Free-Suspended Membrane

To overcome the main disadvantage of classical membrane pressure transmitters, that is uncontrolled mechanical stresses arising in the membrane due to its rigid fixation, and to increase the sensitivity and expand the dynamic range, a precision pressure transmitter for OAD has been proposed. This transmitter is based on a square conductive membrane element freely suspended at four points using elastic sensing elements, which are rigidly fixed to a support frame with a capacitance displacement sensor for the membrane element.

The structural diagram of the opto-acoustic detector of infrared and THz radiation with a free-suspended membrane is shown in Fig. 3. It comprises a cylindrical housing containing a system of an expansion chamber and a compensation chamber that are pneumatically connected and filled with helium at low pressure. One end of the expansion chamber serves as an input window with an anti-reflection coating. Inside the expansion chamber, parallel to the input window, is a collodion film with a metal absorbing element in the form of a thin metallic film deposited on it and thermally isolated from the expansion chamber walls. The expansion chamber is separated from the compensation chamber by a dividing partition, which is a disc-shaped thin elastic plate of conductive material secured between a support washer and a clamping washer. The diameter of the dividing partition is equal to the inner diameter of the compensation chamber. Four through-etched lines, each

3–30 μm wide, are made on the dividing partition (Fig. 4) using the precision photolithography technology. Each line consists of two orthogonal, equal-length segments of length a . The first segment starts at distance b from the corner of the central square ($a \times a$) and is oriented along the square side. The second segment is made at a 90° angle to the first and runs parallel to the square side with an offset equaling to $b + \Delta$, where Δ is the width of the gap formed by the through etching. This process forms:

- non-deformable membrane element 15 of the square shape ($a \times a$), with side $a = 0.6D$, located at the center of dividing partition 9 and covering most of the acoustic aperture and is capable of moving translationally along an axis perpendicular to its plane under the pressure of the expanding gas.

- a four-point corner elastic suspension in the form of four narrow ($a \times b$) elastic sensing elements 10 positioned along the lateral sides of non-deformable square membrane element 15 and rigidly fixed to the support frame;

- support frame 9 representing the peripheral part of the dividing partition secured with clamping washer 18.

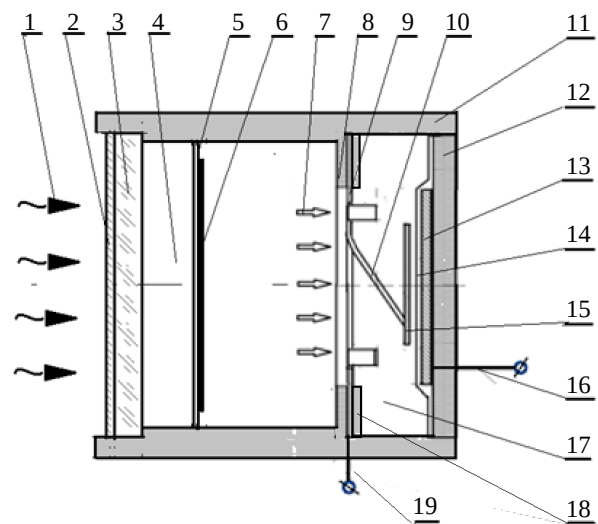


Fig. 3. Structural diagram of the opto-acoustic receiver of infrared and THz radiation with a free-suspended membrane: 1 – input radiation; 2 – anti-reflection coating; 3 – input window; 4 – expansion chamber; 5 – film with through porosity; 6 – metal absorbing element; 7 – pressure wave; 8 – washer-shaped partition; 9 – support frame; 10 – elastic sensing element; 11 – cylindrical housing; 12 – rear wall of the compensation chamber; 13 – fixed electrode of the dynamic capacitor; 14 – protective dielectric coating; 15 – non-deformable square membrane element; 16 – fixed electrode terminal;

17 – compensation chamber; 18 – clamping washer; 19 – dividing partition terminal

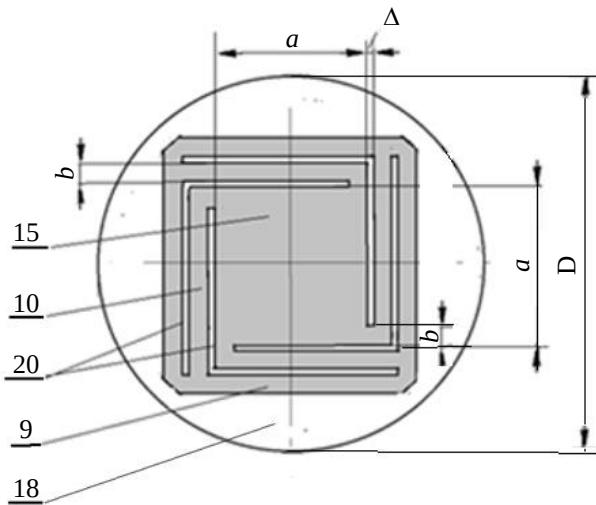


Fig. 4. Structural diagram of the sensitive element of the pressure transmitter with a free-suspended membrane element, where 9 – support frame of the sensitive element, 10 – elastic sensing beam, 15 – non-deformable square membrane element, 18 – clamping washer, 20 – through-etched line

Under the pressure of the expanding gas, each of four sensing elements 10 will experience bending deformations caused by: distributed load: $\delta_{\text{distr.}} = qa^4/8EI$, where $\delta_{\text{distr.}}$ is the sensing element's deflection; q is the specific pressure; a is the sensing element's length; E is the elastic modulus of material; I is the moment of inertia of the rectangular cross-sectional area of the sensing element $I = bh^3/12$, and concentrated load caused by pressure P on one quarter of membrane element's area $\delta_{\text{conc.}} = QEI \frac{a^3}{3}$, where $Q = 0.75Pa^2/4$ and $h_{\text{conc.}} = 0.75Pa^5/Ebh^3$.

The total displacement of the corner of non-deformable membrane element 15 will be $\delta = \delta_{\text{distr.}} + \delta_{\text{conc.}}$. With sensing elements being completely identical, this ensures the translational movement of non-deformable square membrane element 15, which serves as a traveling electrode in the capacitance pressure transmitter.

The sensitivity of such pressure transmitter is determined by sensing elements' width b , where $b = (0.1-0.05)a$, and dividing partition

thickness h , which is equal to several micrometers.

Expansion chamber 4 and compensation chamber 17 become pneumatically connected through the gaps of the through-etched lines in the dividing partition. This provides pneumatic feedback between the chambers similarly to a capillary channel in the classical OAD scheme, and eliminates the stiffness increase due to gas compression in compensation chamber 17.

Conclusion

The proposed free-suspended membrane forms a third group of sensing elements for opto-acoustic detectors (OAD) (membrane, cantilever, free suspension). A similar free suspension is known as a 4-point Z-shaped skew-symmetric suspension for axial accelerometers [17]; however, it has not been considered as a membrane suspension for pressure transmitters in the known literature. This suspension provides the sensitivity increased by more than three orders of magnitude as compared to a circular membrane made of the same material and having the same thickness and active area. The translational movement of the freely suspended conductive membrane element ensures the effective conversion of pressure changes in the expansion chamber into capacitance changes. If a dashed reflective mask is applied on the membrane element surface, the suspension, due to its rotational motion, simultaneously allows for optical readout of the displacement using the Toepler "schlieren" technique.

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REFERENCES

1. Gibin I. S. and Kotlyar P. E., Applied Physics, № 2, 90–97 (2020) [in Russian].
2. Kotlyar P. E. and Potaturkin O. I., Avtometriya, № 3, 77–95 (2025).
3. Andreyeva L. Ye. Uprugiy elementy priborov. Moscow, Mashinostroyeniye, 1981, p. 463.

4. Hasikin K., Soin N. and Ibrahim F. Proc. of the IEEE Int. Conference on Semiconductor Electronics. Malacca, Malaysia, 2010, pp. 293–296.
5. Palatnik L. S. and Il'inskiy A. I., UFN **95** (4), 613–645 (1968).
6. Dedkova A. A. et al., Zhurnal tekhnicheskoy fiziki **91** (10), 1054–1465 (2021).
7. Poliimidnyye plenki DuPont™ Kapton®. www.dupont.com. 03.04.2023.
8. Baglioni G. et al., Nanoscale **15**, 6343–6352 (2023).
9. Fan K., Suen J. Y. and Padilla W. J., Opt. Express **25** (21), 25318–25325 (2017).
10. Tun P'o Vin., Simonov B. M. and Timoshenkov S. P., Izvestiya vuzov. Elektronika **28** (2), 222–231 (2023).
11. de Paula M. H. et al., J. Appl. Phys. **64**, 3722–3724 (1988).
12. Getmanenko N. Yu., Vostochno-Yevropeyskiy zhurnal peredovykh tekhnologiy **4/7** (52), 30–35 (2011).
13. Mikko Saarinen. Cantilever enhanced gas sensing using photoacoustic spectroscopy. Finland, Aalto university school of science and technology, 2010, p. 83.
14. Lindley R. E. et al., Applied Physics B **86**, 707–713 (2007).
15. Bykov A. V., Izvestiya Yuzhnogo federal'nogo universiteta. Tekhnicheskkiye nauki, 141–151 (2014).
16. Feodos'yev V. I. Izbrannyye zadachi i voprosy po soprotivleniyu materialov. Moscow, Nauka, 1967.
17. Raspopov V. Y. Mikromekhanicheskiye pribory. Moscow, Mashinostroyeniye, 2007.

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