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Effect of internal mechanical stresses in a multilayer structure on displacement for various designs of microelectromechanical membranes

S.V. Malokhatko[1]✉, E.Yu. Gusev[1], Jiang L.[2], O.A. Ageev[1]

[1] Institute of Nanotechnology, Electronics and Electronic Equipment Engineering, Taganrog, Russia;

[2] Laser Institute, Qilu University of Technology, Shandong Academy of Sciences, Jinan, China

✉ malohatko@sfedu.ru

Abstract. In the manufacture of microelectromechanical sensors based on multilayer membranes, internal mechanical stresses arise in the structure. A preliminary assessment of the effect of internal mechanical stresses on the initial displacement of structures of various shapes will allow to choose the most appropriate design solution for various applications. The paper presents the results of numerical modeling of the structures of multilayer membranes of three types: round, square and square with transverse and angular beams. The displacement values for each type of multilayer membranes are obtained in accordance with the influence of internal mechanical stresses in each layer. The results showed that the effect of internal mechanical stresses in films (SiO_2, Mo, ZnO) of a multilayer structure on square and round membranes is insignificant (values ranged from $2.43 \cdot 10^{-13}$ to $7.83 \cdot 10^{-13}$ nm). Internal mechanical stresses in membrane layers with transverse and angular beams make a significant contribution to the initial displacement of the structure (values ranged from 20 to 570 nm), however, the sensitivity of such structures is higher than that of rigid structures. The influence of technological conditions of film formation in multilayer membranes on their stress-strain state in ultrasonic sensors is investigated. The values of internal mechanical stresses in SiO_2 films are obtained.

Keywords: microelectromechanical sensors, multilayer membrane, internal mechanical stress

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Влияние внутренних механических напряжений в многослойной структуре на смещение для различных конструкций микроэлектромеханических мембран

С.В. Малохатко[1]✉, Е.Ю. Гусев[1], Цзян Л.[2], О.А. Агеев[1]

[1] Институт нанотехнологий, электроники и приборостроения (ЮФУ), г. Таганрог, Россия;

[2] Лазерный институт, Технологический университет Цилу, Шаньдунская академия наук, Цзинань, Китай

✉ malohatko@sfedu.ru

Аннотация. В работе представлены результаты моделирования конструкций многослойных мембран трех типов: круглой, квадратной и квадратной с поперечными и угловыми подвесами. Получены значения прогиба для каждого типа многослойных

мембран по действие внутренних механических напряжений в каждом слое. Исследовано влияния технологических условий формирования пленок в многослойных мембранах на их напряженно-деформированное состояние в ультразвуковых датчиках.

Ключевые слова: микроэлектромеханические датчики, многослойная мембрана, внутреннее механическое напряжение

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Introduction

Microelectromechanical devices cover more and more fields of application [1]. Such devices include ultrasonic microelectromechanical sensors (includes piezoelectric micromachined ultrasonic transducers) that can be used for industrial and medical purposes [2]. The output characteristics of such devices depend on a sensing element consisting of a multilayer membrane-type structure. By changing the membrane design, certain functional parameters of the sensor can be improved [3]. However, at the stage of multilayer structure fabrication, under the influence of various factors, internal mechanical stresses arise in the layers, which lead to displacement of structures without external influence [4]. The displacement of the structure leads to a decrease in sensitivity. Thus, an actual task is to study the effect of internal mechanical stresses on the displacement of a multilayer membrane, depending on its design.

A previously conducted assessment on the influence of physical and mechanical parameters of the base materials on the resonant frequency for the typical (widely used [2,3]) structure Si/SiO_2/Metal/Piezoelectric/Metal showed the promise and technological feasibility of using zinc oxide and molybdenum which also have high resistance and strength.

Materials and Methods

Modeling in the Comsol Multiphysics was carried out for three types of membranes: round (diameter of 500 μm), square (side length of 500 μm) and square with transverse and angular beams (length of 50 μm, width of 25 μm). The multilayer structure included the following layers $Si/SiO_2/Mo/ZnO$ (50/2/0.1/0.1 μm). The internal mechanical stresses that were taken into account during the simulation ranged from -80 to -500 MPa [5], from -1.5 to +1.5 GPa [6] and from -0.7 to +0.7 GPa [7] for SiO_2, Mo and ZnO films, respectively. The fabrication of SiO_x films was carried out by plasma chemical deposition from the gas phase [8]. Further, the obtained films were subjected to rapid thermal annealing at a temperature of 600 °C for 3 minutes.

Results and Discussion

Fig. 1 shows the displacement of a square membrane and a square membrane with transverse and angular beams under the action of internal compressive stresses of -100 MPa in the SiO_2 layer.

Depending on the internal mechanical stresses in the multilayer structure, displacement values are obtained for each type of membrane, which are presented in Table 1.

As can be seen from the results obtained, the more rigid the fixation of the membrane, the less the effect of internal mechanical stresses on the initial displacement of the membrane. However, square membranes with angular and transverse beams have higher sensitivity. The mechanical sensitivity of square membranes and square membranes with angular and transverse beams under the influence of an external pressure of 5.19 kPa was 0.05 nm/kPa and 0.26 nm/kPa, respectively. This behavior is due to the direct dependence of the rigidity of the structures on the type of membrane attachment.

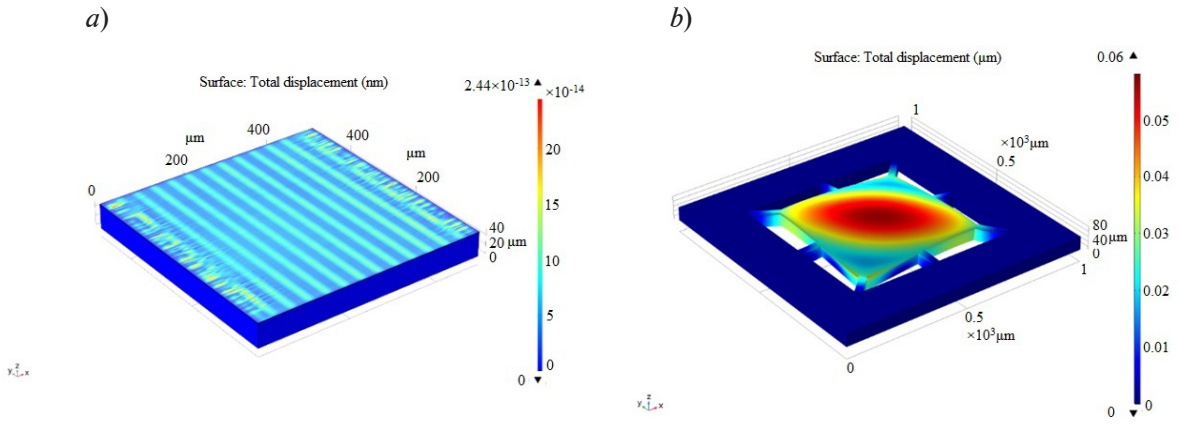

Fig. 1. Displacement of membranes: square (*a*) and square with transverse and angular beams (*b*) under the action of internal compressive stresses of −100 MPa in a SiO_2 film

Table 1

Displacement values of the multilayer membrane, nm

Membrane shape	Layer		
SiO_2		Mo	ZnO
	From –80 to –500 MPa	From -1.5 to +1.5 GPa	From -0.7 to +0.7 GPa
Round	From $2.95 \cdot 10^{-14}$ to $2.72 \cdot 10^{-13}$ (↑)	From $4.35 \cdot 10^{-13}$ (↑) to $5.23 \cdot 10^{-13}$ (↓)	From $2.64 \cdot 10^{-13}$ (↑) to $2.63 \cdot 10^{-13}$ (↓)
Square	From $7.83 \cdot 10^{-13}$ to $5.09 \cdot 10^{-13}$ (↑)	From $6.23 \cdot 10^{-13}$ (↑) to $6.23 \cdot 10^{-13}$ (↓)	From $2.44 \cdot 10^{-13}$ (↑) to $2.43 \cdot 10^{-13}$ (↓)
Square with transverse and angular beams	From 20 to 570 (↑)	From 90 (↑) to 90 (↓)	From 40 (↑) to 40 (↓)

The average value of mechanical stresses in the SiO_x films obtained was -168±5 MPa, which is consistent with theoretical data [5]. Thus, with the streamlined process of obtaining multilayer structures at the design stage, it becomes possible to consider the influence of internal mechanical stresses in each layer on the output characteristics of microelectromechanical membranes.

Conclusion

The analysis of the results showed that for the development of microelectromechanical sensors based on multilayer membranes with increased sensitivity, it is necessary to use structures partially released along the perimeter. However, due to the significant contribution of internal mechanical stresses to the initial displacement of such structures, their consideration is required at the design stage of the structure. The obtained results can be extended to multilayer Si/SiO_2/Metal/Piezoelectric/Metal structures with another material of the piezoelectric and metal layers. The presented results can be used to optimize the designs and fabrication processes of multilayer structures used in acoustic sensors, micromirrors and resonators.

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THE AUTHORS

MALOKHATKO Sofya V.
malohatko@sfedu.ru
ORCID: 0000-0001-7989-6513

JIANG Liyuan
jiangliyuan@sdlaser.cn

GUSEV Evgeny Yu.
eyugusev@sfedu.ru
ORCID: 0000-0001-8635-2573

AGEEV Oleg A.
ageev@sfedu.ru
ORCID: 0000-0003-1755-5371

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