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DESIGN OF BOSSED SILICON MEMBRANES FOR HIGH SENSITIVITY MICROPHONE APPLICATIONS

P. Martins[1], S.Beclin[2], S.Brida[2], S.Metivet[2], O.Stojanovic[2], C. Malhaire[1]

1: LPM, UMR 5511, INSA Lyon, 7 av. Capelle bât. B. Pascal, 69621 Villeurbanne, France
2: Auxitrol SA, Esterline Sensors Group, Esterline Corporation 5, Allée Charles Pathé, 18941 Bourges Cedex 9, France

ABSTRACT

This paper deals with the design optimization of new high sensitivity microphones in SOI technology for gas sensing applications. A novel geometry of bossed silicon membranes used as mechanical transducer has been studied by Finite Element Modelling. Device fabrication is achieved from SOI substrates through deep backside anisotropic etching and shallow front side RIE to define a bossed sensing membrane with two reinforced areas. Thus, the influence of thin film stresses on the device performance is largely decreased. Polysilicon gauges are located on the reinforced areas to get a better linearity in pressure.

1. INTRODUCTION

Bulk micromachined silicon membranes are widely used in various MEMS devices like pressure sensors for automotive or aerospace applications. The use of Silicon On Insulator (SOI) substrates enable the achievement of thin membrane with reproducible and well controlled thickness. Some of the innovative MEMS microphone designs use ultra thin membranes [1] to convert pressure sound waves to electrical energy [2]. Unfortunately, these membranes are very sensitive to the stress state of the thin films deposited on top of them.

Indeed, after test on a first microphones generation, the results obtained were not those expected because of nitride and oxide layers that caused gauge deformations which could not be driven freely anymore (Fig. 1). Consequently, we had a low sensitivity despite the use of very fine membrane thicknesses.

We present in this paper the design optimization of bossed silicon membranes used as mechanical transducer [3]. The mechanical behaviour of the membranes has been studied by Finite Element Modelling. The electrical transducer (piezoresistive gauges) design has been optimized to get a high sensor sensitivity with a good linearity.

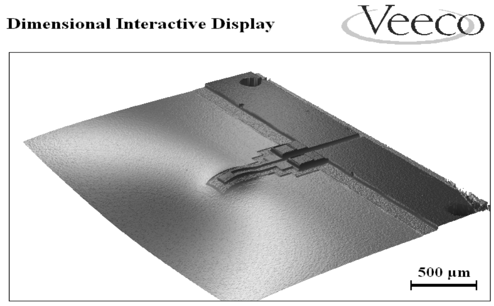

Figure 1. Gauge deformation due to thin film stresses.

After packaging, the devices were characterized in terms of linearity, frequency response and power consumption. A sensitivity of 105 µV.Pa^{-1}.V^{-1} has been reached.

2. WORKING PRINCIPLE

As shown in Fig. 2, the electrical transducer consists on four dielectrically-isolated, silicon piezoresistors connected in a half Wheatstone bridge configuration. The piezoresistors are deposited on a 100 nm thick thermal oxide on the top of an SOI wafer in order to achieve a complete electrical insulation. The mechanical waves are transformed into an electrical signal by the silicon piezoresistor placed on the membrane in such a way as to maximise the signal.

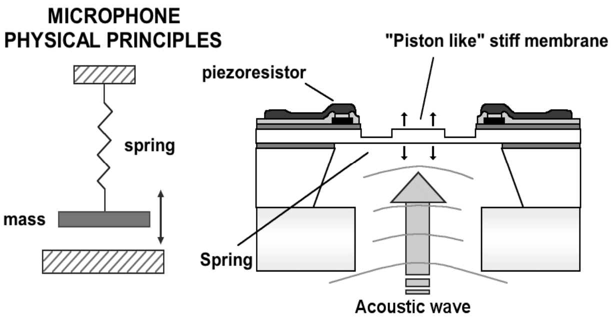

Figure 2. Device cross section schematic.

The mechanical stress produced by the deformation of the membrane is converted to a resistance change by the piezoresistive effect. The relative resistance change can be related to the mechanical stress by the following equation [4]:

$$\Delta R/R = \Sigma \pi i \, \sigma i \tag{1}$$

Where σi are the stress and πi are the piezoresistive coefficients along the i direction, respectively. A positive stress causes a positive variation of resistance; a negative stress causes a negative variation of resistance. In the Wheatstone bridge configuration (Fig. 3) only two resistors Rm are placed on the membrane (where stress is positive) while the other two are placed outside the membrane where one can assume there is no stress contribution.

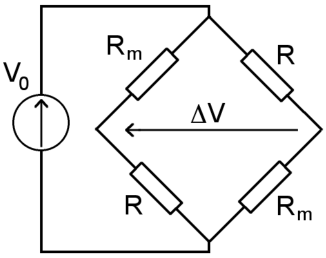

Figure 3. Wheatstone bridge resistor configuration.

Without applied pressure, the bridge is balanced and the output voltage is zero. As the membrane bends under pressure, a stress is induced and the resistance of the two resistors Rm placed on the active area increases. The voltage drop at the output nodes of the bridge is:

$$\Delta V = V_0 \cdot \Delta Rm/R \tag{2}$$

Where ΔRm/R is the relative resistance change and V_0 is the bias voltage. The pressure sensitivity S of the device is therefore defined as:

$$S = \Delta V / (\Delta P \cdot V_0) = \Delta Rm/R \, (1/V_0) \tag{3}$$

3. DESIGN OPTIMIZATION BY FINITE ELEMENT MODELLING

The difficulty to obtain good sensitivities with the first generation of microphones constrained us to study a new generation of microphones with different geometric parameters for mechanical and electrical transducer.

3.1. Mechanical transducer

A special configuration of the membrane has been designed to minimize the mechanical instability of the resistor and at the same time to increase its sensitivity to the applied pressure. The idea consists of designing a thin square membrane with a thicker circular central area (2-3 times thicker). Two reinforced “arms” are designed to mechanically connect the central part to the membrane edges (Fig. 4). The piezoresistors would be deposited on top of these reinforced parts, close to the membrane edge where the strain is higher. The strain distribution over the reinforced parts would be more uniaxial and extended on a larger area compared to that for a membrane with a constant thickness.

The software package ANSYS, based on the finite element method (FEM), has been used to calculate the strain distribution all over the membrane. Different geometries have been studied in order to provide information in terms of linearity and sensitivity. As shown in Fig. 4 the geometrical parameters are: the circle diameter D, the cross-pieces width W and the membrane thicknesses ratio. These studies have been made for circle diameter varying between 500 μm and 1100 μm, the cross width varying between 100 μm and 180 μm and for the membrane thicknesses ratio varying between 1/3 and 3/4. The thickest membrane area was fixed at 6 μm (SOI top silicon layer thickness). Due to symmetry, only a quarter of the membrane has been simulated.

As shown in Fig. 5, the FE simulations confirmed that strains were concentrated at the beginning of the cross-pieces. The circle diameter has to be the as larger as possible (1100 μm) in order to get the best results (Fig. 6) and the cross-pieces has to be the narrowest possible i.e. 120 μm (limited by the width of PSOI gauge). Moreover, the membrane thicknesses ratio has to be as greater as possible (Fig. 7). During the microphones fabrication, thicknesses ratio down to 1/10 have been obtained (thinner and thicker membrane area thicknesses of 0.5 and 5 μm, respectively) leading to the highest sensitivity.

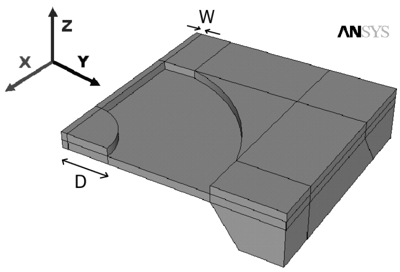

Figure 4. Membrane geometry (not to scale).

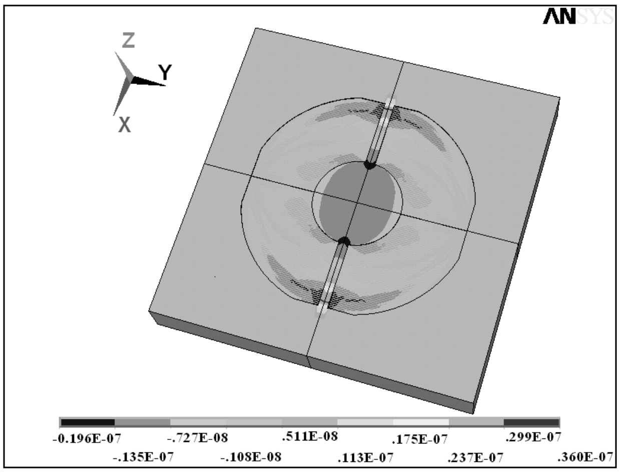

Figure 5. Simulated x-direction strain mapping on top of the membrane.

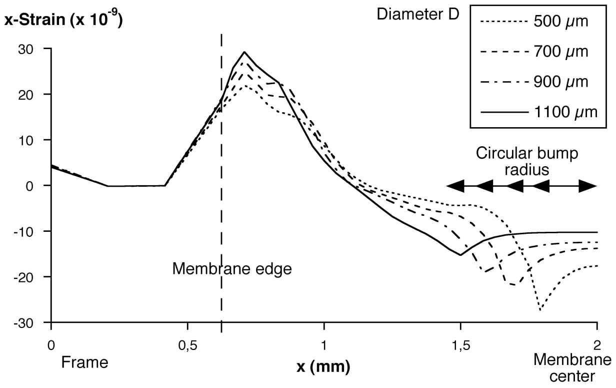

Figure 6. Strain evolution along the x-axis as a function of boss diameter for a pressure of 100 mPa.

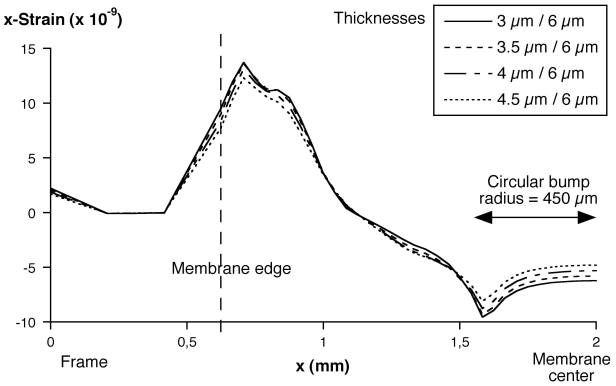

Figure 7. Evolution of the strain with the ratio thicknesses for a pressure of 50 mPa.

Figure 8 shows the simulated average strain at the gauge location (on top of the cross-piece near the membrane edge) as the function of the applied pressure. A good linear behaviour of the mechanical transducer has been pointed out in the [0 - 1000 mPa] range. If we assume that these deformations are fully transmitted to gauges, a microphone linear electric response could be obtained (see paragraph 5).

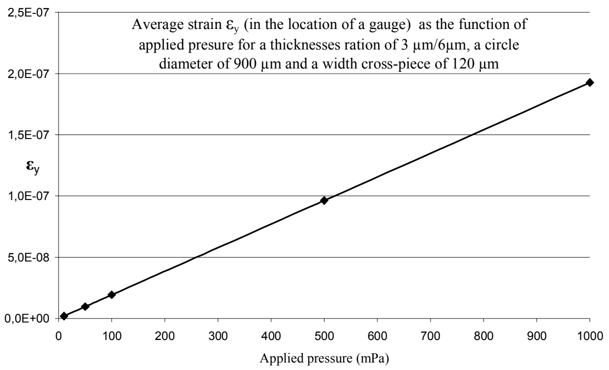

Figure 8. Simulated average strain for a fixed location close to the membrane edge as a function of the applied pressure.

3.2. Electrical transducer

In order to reduce the gauge deformations when the membrane is refined, a new front side layout has been developed to reduce the nitride and oxide layers influence. Moreover, to increase the sensitivity, the gauges were narrowed in their centre to make them more compliant (Fig. 9).

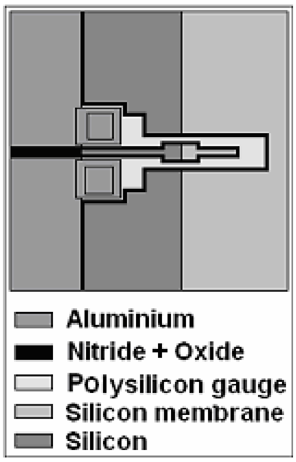

Figure 9. Gauge design modifications.

4. FABRICATION PROCESS DESCRIPTION

For the fabrication process we used SOI silicon wafers with a diameter of 100 mm and a thickness of 525 µm. The thickness of SOI was 5 microns; the thickness of silicon oxide for insulation is 400 nm.

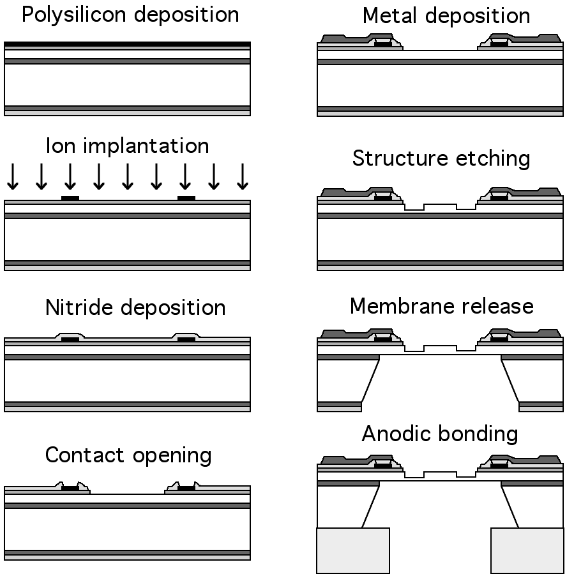

Figure 10. Main fabrication process steps.

A 7-mask process has been developed and is schematically illustrated in Fig. 10. The SOI wafers are cleaned and a screen oxide (100 nm) is grown at 1000 °C in pure oxygen. Then a succession of LPCVD polysilicon deposition, resistor lithography and ion implantation step is performed to define and to dope the p resistors. To electrically insulate the gauge, a 50 nm thick thermal oxide layer is grown and a 100 nm thick LPCVD silicon nitride is deposited. A mask is patterned to define the anodic bonding tracks. At this point the contact holes are opened and a 600 nm TiW/Aluminium metallization coating is sputtered and patterned. The front side of the wafer is etched in order to define the 3D structures on the membrane (Fig. 11 and 12). The etching windows to define the membrane size are patterned and opened on the backside masking layers. A timed anisotropic etching forms the membranes. The sensing membranes are etched in (100)-oriented silicon by anisotropic etching using an aqueous KOH solution. Finally the wafers are diced and the sensors chips are packaged for testing.

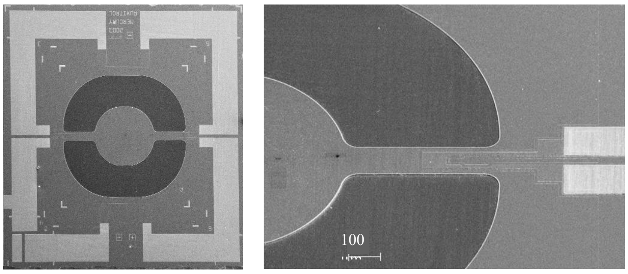

Figure 11. Top view of a simple bossed silicon membrane that have been studied by FE simulations.

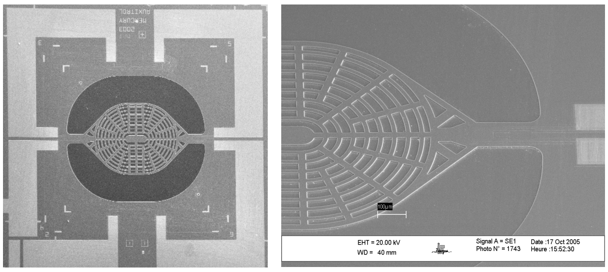

Figure 12. Optical and SEM photographs of a piezoresistor on the cantilever structure after fabrication process.

Complementary tests have also been performed on “tennis racket” like bossed membrane (Fig. 12) with the same geometrical parameters than a simple bossed membrane. The aim was to change slightly the stiffness of the bump and see the influence on the device sensitivity.

As shown by interferometric spectrometry measurements (WYCO NT 1100 in fig. 13), only the thin part of the membrane was strained without any effects on the gauges. Moreover, the membrane thicknesses ratio was about 500 nm to 5 µm.

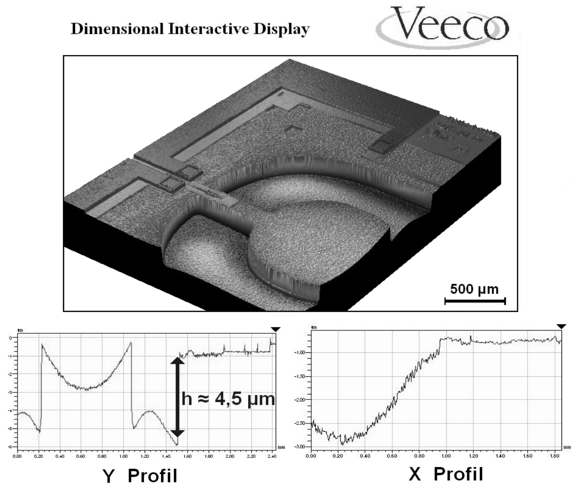

Figure 13. Spectroscopic interferometry image of a microphone (above) and profilometers along two axes where the thicknesses are extracted (below).

5. RESULTS AND DISCUSSION

The characterisation of microphone frequency (less than 50 Hz) requires special testing equipment. For this reason a dedicated testing tool has been designed. This tool is based on a volume variation principle in order to generate the required small pressure variations by using a PZT ceramic under an applied sinusoidal voltage at a frequency of 30 Hz.

A complete set of characterisation curves of the microphone devices has been made. The results obtained in terms of output voltage ΔV of the Wheatstone bridge and sensitivity as a function of the pressure are shown in Fig. 14. The measurements have been repeated several times over the same range of applied pressure.

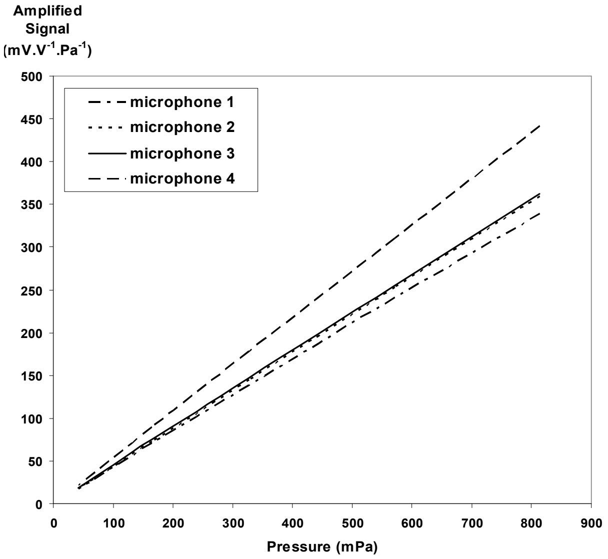

Figure 14. Measured potential microphone as a function of applied pressure.

The results of the continuously repetitive tests show the absence of hysteresis effects for all the different thickness of the tested membranes. All the microphones exhibit a very good linearity in agreement with the mechanical transducer FE simulations. We can observe a linear answer corresponding to the FE simulations (Fig. 8). High sensitivities up to 105 $\mu V.V^{-1}Pa^{-1}$ have been achieved. It has been checked that the frequency response for all the microphones with different design is flat from 3 Hz to 600 Hz.

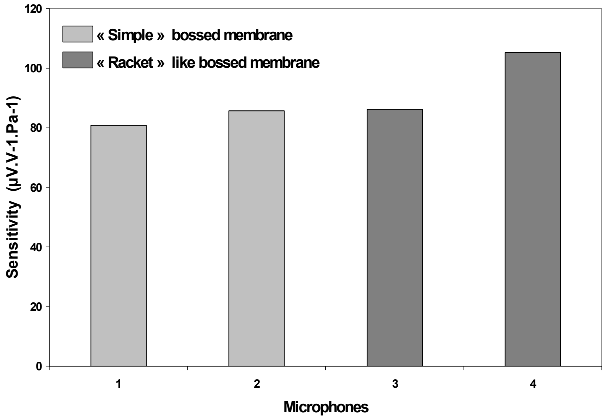

Figure 15. Assessment of sensitivities per microphone.

Fig. 15 shows the different measured sensitivities. The highest measured sensitivity value was 105 $\mu V.V^{-1}.Pa^{-1}$. It can be noted that these results are not homogeneous, moreover there is no significant difference between devices with "racket" or "simple" bump. The slight discrepancy of these results can be explained by the Reactive Ion Etching (RIE) step that has been performed separately on each device after dicing leading to a thickness error about 10%.

6. CONCLUSIONS

A fabrication process for the realisation of silicon piezoresistive microphones has been developed. This process includes the etching of a complex bossed silicon membrane to decrease the influence of the thin film stresses and increase the sensor sensitivity. In spite of the use of SOI substrates, the front side RIE step is crucial as it defines the stiffness of the membrane then the sensor sensitivity. The encouraging preliminary results obtained in terms of sensitivity demonstrate the feasibility of the technological process for piezoresistive microphones and are the starting point for the future engineering of sensors aimed to specific applications.

7. ACKNOWLEDGEMENTS

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