NEW PIEZORESISTIVE SILICON HIGH PRESSURE SENSOR

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Abstract: For current known piezoresistive silicon pressure sensors, the pressure to be measured is transformed into an elastic deformation of the strongly bounded silicon diaphragm. The resistance value of the implanted piezoresistors on the silicon diaphragm is modified through the resulted mechanical tensions on the material. The etched silicon diaphragm demonstrates a limited burst tension, so that the usual silicon pressure sensors with a diaphragm can only be utilised to measure a maximal pressure of 10^3 bar.

The pressure sensitive element is made up of a not thinned silicon chip with piezoresistors on its upper surface and of a whole-surface glass substrate (Pyrex) bonding connection on its bottom side. The different Young moduli of Silicon and Pyrex implies, by all sided-pressure load, the appearance of mechanical tensions in the bounding surface between the two materials. These mechanical tensions in the silicon chip produce a modification of the piezoresistor resistance implanted in the upper surface because of the piezoresistive effect.

Keywords: piezoresistive, high pressure sensor

1 INTRODUCTION

Due to their simple construction and their large output signal, piezoresistive silicon sensors take a primacy within pressure sensors. Nowadays piezoresistive pressure sensors are available for different nominal pressure areas from 10 mbar up to 1000 bar and can therefore be used for different applications. Thus, they are used in medical technology e.g. for blood pressure measurements and car electronics for monitoring the suction and brake pressure.

The upper boundary of the nominal pressure area is achieved at max.10^3 bar and is caused by the limited burst tension value, which is conditioned by the etching of the silicon plate. This crucial disadvantage combined with the high manufacturing cost of the silicon plate and the high effort for the prerequisite special etching and covering devices justify the necessity to search for new solutions.

In this paper a new piezoresistive pressure measuring element is presented which eliminates these disadvantages. The measured element consists of an unthinned silicon chip with piezoresistors on its upper surface and of a whole-surface borosilicate glass substrate Pyrex [1] bonding connection on its bottom side. The principle effect of this new high pressure sensor is based on the different elasticity characteristics of the employed materials. Due to the different Young moduli of silicon and Pyrex the mechanical tensions which occur on the silicon chip surface, when it is exposed to an all- sided pressure, can be measured thanks to piezoresistors.

2 THEORETICAL PRINCIPLES

In the following paragraph, we shall calculate the normalized resistance change of two piezoresistors mounted on the upper surface of (100) silicon in the case of an all-sided – hydrostatic – pressure load.

If the homogeneous body shown in figure 1, is exposed to the same pressure p on all sides, the normal tensions T_1, T_2, T_3 which occur in its volume are:

$$\begin{aligned} T_1 &= T_2 = T_3 = -p \\ T_4 &= T_5 = T_6 = 0 \end{aligned} \qquad (1)$$

The piezoresistive effect leads to a dependency of the specific resistance tensor (ρ) from the mechanical stress tensor (T) [2]. This dependency is described by the piezoresistive coefficients π_{ik}. Due to the anisotropical structure of silicon, the coefficients π_{ik} depend on the orientation of the piezoresistors in crystal.

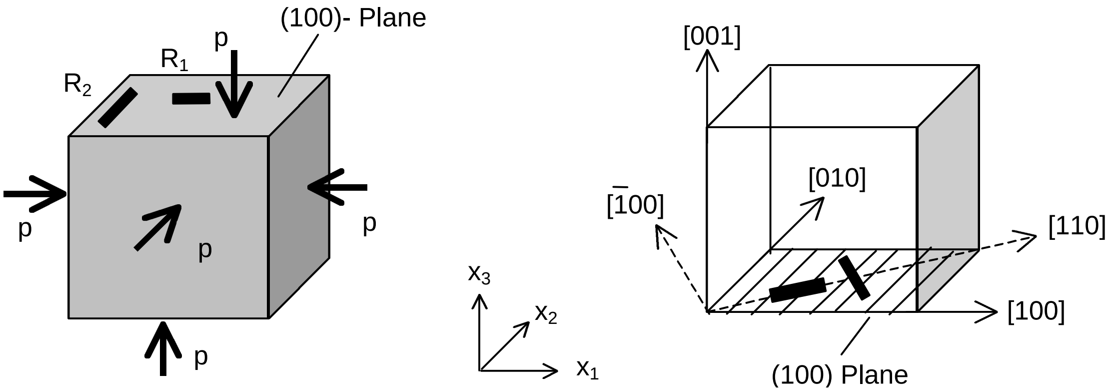

Figure 1. Piezoresistors on a silicon surface of orientation (100), in direction [100].

In the literature [3] the following relation is indicated:

$$\frac{\Delta R_i}{R_i} = \sum_{k=1}^{6} \pi_{ik} \cdot T_k \tag{2}$$

In (2) π_{ik} are the components of the tensor of piezoresistive coefficients and T_k are the components of the stress tensor.

Taking the cubic symmetry of the silicon crystal ($\pi_{13} = \pi_{23} = \pi_{12}$) into consideration, the following can be deducted for the normalized resistance changes r_1 and r_2 for both piezoresistors R_1 and R_2:

$$r_1 = r_2 = \frac{\Delta R_i}{R_i} = \frac{1}{2}\left(\pi_{11}+\pi_{12}+\pi_{44}\right)T_1 + \frac{1}{2}\left(\pi_{11}+\pi_{12}-\pi_{44}\right)T_2 + \pi_{12}T_3 = -\left(\pi_{11}+2\pi_{12}\right)p, \quad T_1 = T_2 = T_3 = -p \tag{3}$$

In the present case of the hydrostatical load an equal change of the normalized resistance changes of the piezoresistors R_1 and R_2 occurs. So, if the piezoresistors are arranged as a Wheatston bridge, no output signal can be measured.

In the presented example, if the deformation element in a normal direction e.g. x_1, is loaded with a higher pressure of ΔT_1, the normal stresses are modified as follows:

$$T_1 = -p + \Delta T_1$$
$$T_2 = T_3 = -p \tag{4}$$

Substituting these relations in (2) and replacing the π_{ik} coefficients by the values given in the literature [2] results in:

$$r_1 = \frac{\Delta R_1}{R_1} = \frac{1}{2}\left(\pi_{11}+\pi_{12}+\pi_{44}\right)\left(-p+\Delta T_1\right) + \frac{1}{2}\left(\pi_{11}+\pi_{12}-\pi_{44}\right)(-p) + \pi_{13}(-p) = -\left(\pi_{11}+2\pi_{12}\right)p + \frac{1}{2}\pi_{44}\Delta T_1 \tag{5}$$

$$r_2 = \frac{\Delta R_2}{R_2} = \frac{1}{2}\left(\pi_{11}+\pi_{12}-\pi_{44}\right)\left(-p+\Delta T_1\right) + \frac{1}{2}\left(\pi_{11}+\pi_{12}+\pi_{44}\right)(-p) + \pi_{13}(-p) = -\left(\pi_{11}+2\pi_{12}\right)p - \frac{1}{2}\pi_{44}\Delta T_1 \tag{6}$$

In (5) and (6) π_{11} and π_{12} as well as their sum ($\pi_{11}+\pi_{12}$) may be neglected because they are much smaller than π_{44} for the given silicon orientation [2].

$$r_1 = \frac{\Delta R_1}{R_1} = \frac{1}{2}\pi_{44}\Delta T_1 \tag{7}$$

$$r_2 = \frac{\Delta R_2}{R_2} = -\frac{1}{2}\pi_{44}\Delta T_1 \tag{8}$$

From the equations (7) and (8) can be deducted that the normalized resistance change is increased or decreased proportionally to the tension difference ΔT_1.

When the piezoresistors are arranged in a DC voltage-fed Wheatston bridge [4], the following output voltage will be reached:

$$u = \frac{1}{4} \cdot \left(r_1 + r_3 - r_2 - r_4 \right) \cdot U_0 \Leftrightarrow \frac{u}{U_0} = \frac{1}{4} \cdot \left(r_1 + r_3 - r_2 - r_4 \right) = \frac{1}{2} p_{44} \Delta T_1 \qquad (9)$$

with $r_1 = r_3$ and $r_2 = r_4$

In (9) u is the output voltage, U_0 is the supply voltage of the bridge and r_1, r_2, r_3 and r_4 are the normalized resistance changes of the four piezoresistors placed on the bridge branches.

If an unthinned silicon chip is mounted with its entire lower surface on a carrier (e.g. Pyrex) and ideally connected with it, then in the case of a hydrostatical pressure, a mechanical additional tension field is produced at the material connection surface. This tension field is attributed to the different elastic characteristics of the two materials. Its calculation is analytically not possible. Using the Finite Elements Method (FEM simulation), the tension field will be calculated for variations of form and of silicon and glass carriers dimensions and will be optimized towards the maximal value.

3 SENSORDESIGN

3.1 Simulations

The theoretical investigations for a new design of a high pressure sensor were carried out by simulations with the finite element program ANSYS [5].

The basic principle of the examined primary sensor is represented in figure 2. A silicon slice is connected with its entire lower surface with a Pyrex body by anodic bonding. Two variants of the basic principle, are the cylindrical and the square forms.

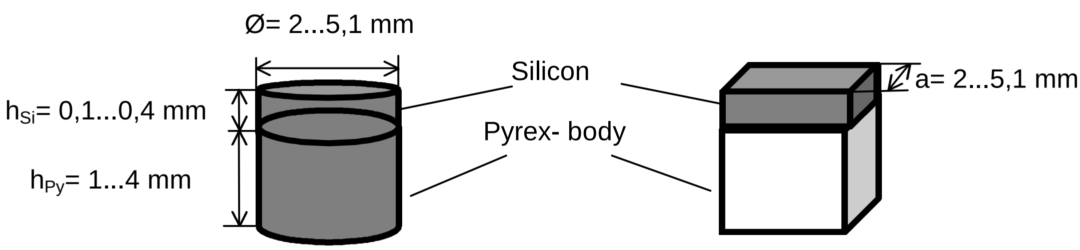

Figure 2. Basic versions of the new measurement element.

On the basis of these versions, further variations were derived and simulated with the objective of finding designs where the higher possible additional tension field at the connection surface of the two materials could be generated. Such variation options arise from constructive measures, like drilling holes into the measurement element.

3.2 Simulation results.

With the simulations of different versions of the new high pressure sensor, the influence of the modification of its geometrical parameters on the transmission factor of the measurement element could be shown. Such varied geometrical parameters were e.g. the form and the dimensions of the silicon slice and the Pyrex substrate.

The fundamental results of the simulation related to the achieved normalized resistance change are:

a) Basically, normalized resistance changes can be derived with different signs for r_1 and r_2 in a range between 0,2% / 10^2 bar and 0,9% / 10^2 bar.
b) In the case of a measurement element fixed on one side, the normalized resistance change is larger than for an all-sided loaded element (hydrostatical pressure).
c) The larger the edge length (diameter) of the measurement element, the larger its normalized resistance change.
d) Drilling holes along the middle axis (only through the Pyrex carrier or through the whole measurement element) results in an increase of the normalized resistance change.
e) The smaller the drilling diameter (in both cases), the larger the normalized resistance change.

3.3 Favourite versions

Taking these results and the minimal production steps and costs into account, experiments were undertaken of the first implementation of the measurement element with the versions represented in figure 3:

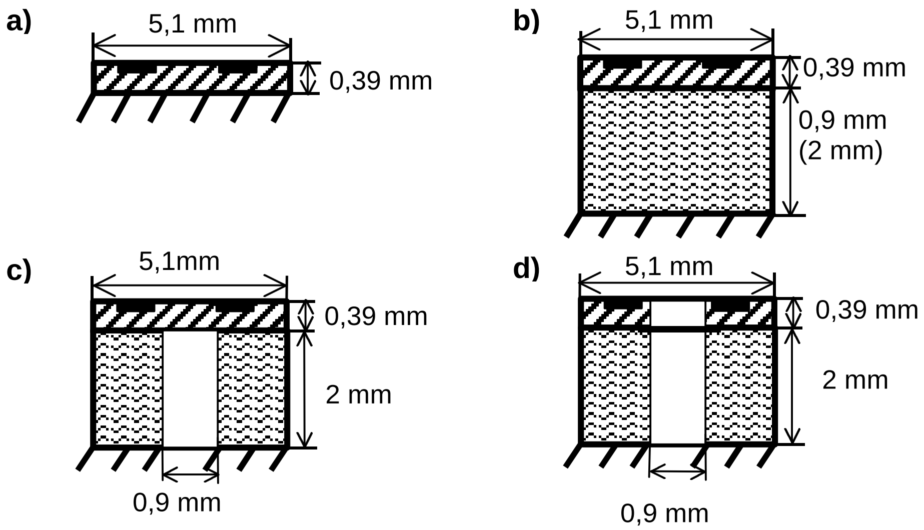

Figure 3. Favorite versions of the high pressure sensor.

The first version (a) is compounded of an unthinned silicon chip fixed on a TO- 8 base. The version (b) represents the connection of a unthinned silicon chip with a Pyrex body. This second version was realized in two variations: i) with one 0,9mm (version (b1)) and ii) with a 2mm thick Pyrex body (version (b2)). In version (c) only the Pyrex body is perforated and in the version (d), the whole element is perforated along its axle center. For all versions, the unthinned silicon chip DS 23 produced by the company Aktiv Sensor [6] has been utilised.

4 EXPERIMENTS

4.1 Measuring program

For the experiments, each sensor was built into a specially constructed reception device and submitted individually to the measuring program presented in Figure 4. The measurements were executed at room temperature with a pressure range from 0 to 100 bar.

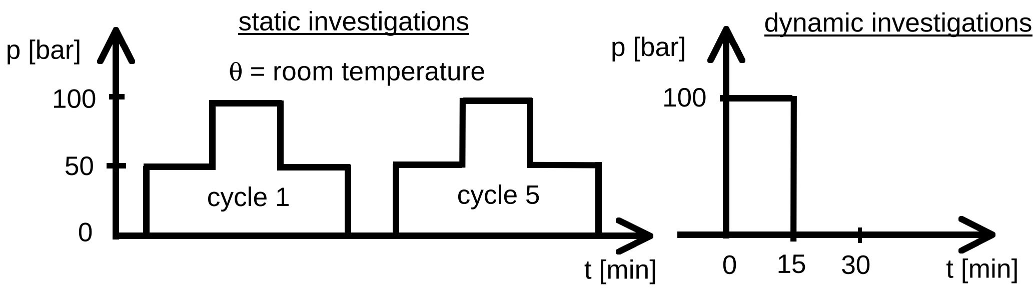

Figure 4. Measuring program.

Aided by this measuring program, the static transmission characteristic and the reproducibility of the results for the measurement elements were obtained. A further experiment was executed after completing the measurements in order to evaluate the long-term stability of the sensors. The sensors were exposed to a constant pressure of 100 bar for a time interval of 15 minutes. During this time, the output voltage was being measured each minute.

The piezoresistors on the sensor elements were connected together in a Wheatstone bridge fed with DC constant voltage. The measured quantity in these experiments was the output voltage of the bridge.

4.2 Results

In figure 5, the measured and the obtained sensitivities through the simulations are compared.

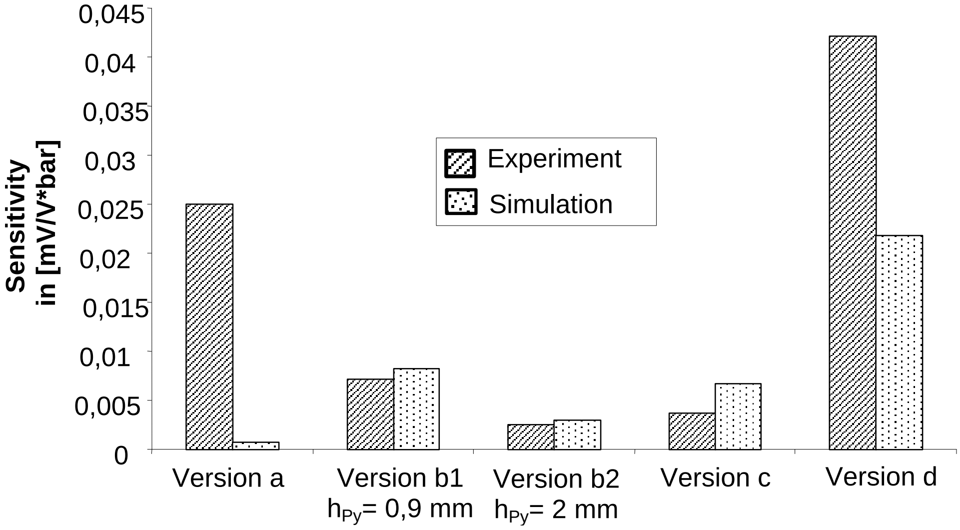

Figure 5. Comparison of simulated and experimental determined sensitivities.

The following conclusions can be derived from the results of the experimental investigations:

a) The connection between the sensor element and the TO- 8 base has a very strong influence on the results. The proof was given by the experiments carried out with the sensor of the first version with a " freely floating " measurement element. After releasing the element from its basis, the output voltage increased significantly.
b) For the version with an approximately 1 mm thick Pyrex body, a large dispersion of the values at the offset voltage as well as for the nominal voltage was observed. The dispersion and the high output voltage can be both again attributed to the influence of the junction area (between measurement element and TO- 8 base) on the results of the measurements.
c) A doubling of the thickness of the Pyrex body led to clearly smaller dispersed values of the zero point and of the nominal voltage. This indicates that the thicker Pyrex body has as result a reduction of the junction influence.
d) The version with a drilling along the middle axis has the highest sensitivity.

In figure 6, the results of the experimental investigations with a perforated measuring element (version d) are represented. During the experiment, the output voltage of the constant voltage-fed Wheatstone bridge (supply voltage U_0 = 5 V) was measured with a load of 0, 50 and 100 bar at room temperature. Five measurement cycles were executed. In each cycle, the load was increased by initial 0 bar in two steps to 100 bar and then down to 0 bar again.

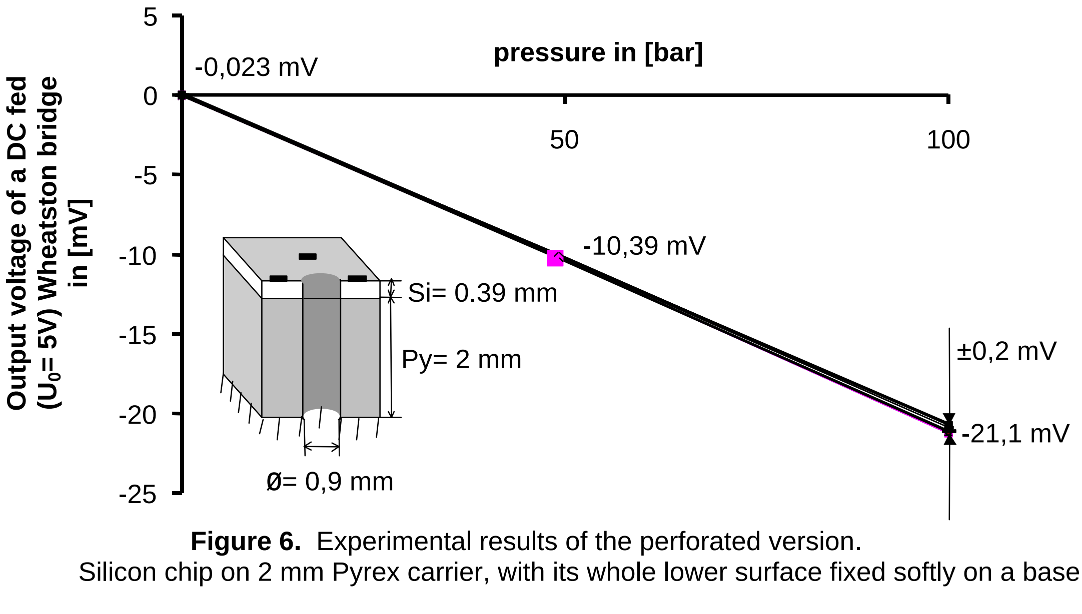

Figure 6. Experimental results of the perforated version.
Silicon chip on 2 mm Pyrex carrier, with its whole lower surface fixed softly on a base.

The measured sensitivity is $4*10^{-2}$ mV/ V* bar. If this measuring element is loaded with a nominal pressure of 1000 bar, under the assumption of a linear increase of the bridge output voltage with the load pressure, it is expected that a nominal output voltage of approx. 200 mV would be observed.

5 SUMMARY

In this work, the development concept of a new piezoresistive high pressure sensor, based on the above described principle, has been presented from the initial idea to the design of several construction suggestions. Based to the experimental results, it can be acknowledged that the new principle is basically suitable for the construction of a high pressure sensor. A corresponding patent has been already announced [7].

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