Novel Silicon High Pressure Sensing Element

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Abstract

This paper presents a working principle for a novel piezoresistive high-pressure sensing element for nominal pressure that amounts from 50 MPa to 500 MPa. The novel overload protected sensing element is made of a solid body silicon chip with implanted piezoresistive resistors. A solid body glass substrate is connected to the silicon chip by holohedral anodic bonding. The operating mode of the novel composite element is based on mechanical strain of the silicon chip and the mechanical mismatched substrate caused by the hydrostatic pressure load. As well metrological and analytical investigations as finite element analyses have been done in order to verify the functionality of the novel composite element. The analytical description is predicated on energy conservation within the multilayer compound. On basis of the analytical approach, the improved geometries of the novel composite element enable repeatable measurement results with a normalized sensitivity of S_n = 25 µV / V MPa. The measuring is realized within a pressure range up to 100 MPa only, due to the mechanical stability of the electrical feed through. The different investigations yield nearly the same result. The deviations reach values smaller than one percent. Thus, the novel operating mode for measuring high-pressure values is confirmed.

Motivation

There is a strong demand for pressure sensors at the international market. Progressive engineering accompanies increasing pressures. High-pressure sensors are used for mass application in cars, for example, for controlling the breaking system (25 MPa) or the common-rail fuel injection system (120 MPa to 300 MPa). Furthermore there are applications like water jet cutting and hydroforming with pressure up to 600 MPa. At the present, the high-pressure range exceed 1 500 MPa for application fields like food-, chemical- and oil industry for example. Therefore novel cost-effective high-pressure sensors should be developed.

State-of-the-art high-pressure sensors are made up of a metal deformation element with strain gauges respectively thin-film circuits for the most part. Thus, the main deficiencies are the difficult and expensive manufacturing of the metal deformation elements. In case of over pressure, the low overload protection results in plastic deformation and as a result in destruction of the whole sensor [1].

State-of-the-art piezoresistive pressure sensors are commonly used for measuring differential und absolute pressure quantities. Due to the limited breaking stress of chemical etched silicon diaphragms the measurable pressure amounts from 1 kPa to 100 MPa only. The advantages of silicon sensors like low-cost high-volume production, mechanical stability of monocrystalline silicon and high sensitivity should also be utilized for the novel high-pressure sensor presented in this paper.

Requirements

Within that project a novel miniaturized overload protected piezoresistive silicon high-pressure sensor is designed, realized, tested and finally optimized. The nominal pressure of the sensing element amounts from 50 MPa to 500 MPa. Table 1 presents an extraction of some further fundamental requirements on the novel high-pressure sensing element presented in this paper.

Table 1: Extraction of requirements on the novel high-pressure sensing element

Requirement	Value
Nominal pressure range p_n	50 MPa to 500 MPa
Overpressure protection p_o	> 600 MPa
Uncertainty of measurement (unbalanced)	< 5 %
Working temperature range	-40 °C to +120 °C
Maximal dimensions of sensing element	3 · 3 · 1 mm³

Operation mode of the novel high-pressure sensing element

In order to meet the requirement of mechanical overload protection, the weak point of the common piezoresistive sensing element has to be eliminated. Accordingly, the novel sensitive element consists of a solid body silicon chip without the regular backside etched silicon diaphragm. A solid body substrate is connected to the silicon by holohedral anodic bonding. There are implanted piezoresistive resistors on top of the silicon chip. This novel sensing element, shown in Figure 1, is called composite element.

One more preference of the novel composite element in order to meet the overload protection is the hydrostatic pressure load. Because of the directionless pressure, there occurs no critical tensile stress within the novel sensing element that implicates destruction.

The substrate of the composite element presented in this paper is a borosilicate glass. Important mechanical properties of used materials are presented in Table 2.

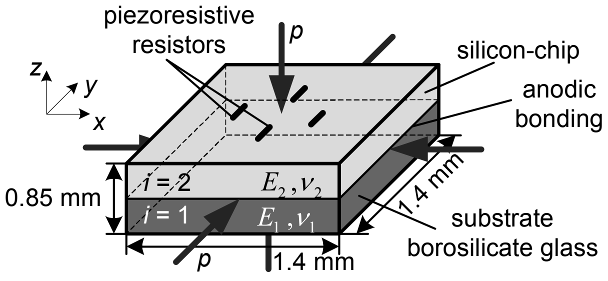


Figure 1: Composite element

Due to the different mechanical properties, both materials of the novel composite element are compressed differently. The glass substrate is softer than the silicon (Table 2), consequently it is compressed more than the silicon chip. Nevertheless, the mechanical strains of both materials have to be the same at theirs interconnect layer due to holohedral anodic bonding. Therefore, the superposition of compression and bending of the multilayer composite element results in shell-shaped deflections.

Table 2: Elastic constants of used materials of the composite element

Material	**Young's modulus *E***	**Poisson's ratio *v***	**Reference**
Silicon, $\langle 110 \rangle$-direction	169 GPa	0.06	[2]
Borosilicate Glass	64 GPa	0.2	[1]

Thus, the operating mode of the novel composite element is based on mechanical strain of the silicon chip and the mechanical mismatched substrate [1, 3, 4]. Due to the different Young's Modulus *E* and Poisson's Ratio *v* of used materials, a pressure-dependant mechanical stress results from hydrostatic pressure load. The shell-shaped deflections of the all-round pressurized composite element cause a change of the resistances by means of the piezoresistive effect [5].

Analytical description

In order to verify the measurement results, presented later on in this paper, and to achieve an approach for optimization, the novel composite element is investigated analytically. The analytical description of the novel composite element is based on energy conservation within an isolated system. The presented approach is similar to that of other multilayered compounds [2, 6]. Due to the all-round pressurized sensing element, a multidimensional analysis is necessary. Figure 2 shows the model of the multilayered composite element.

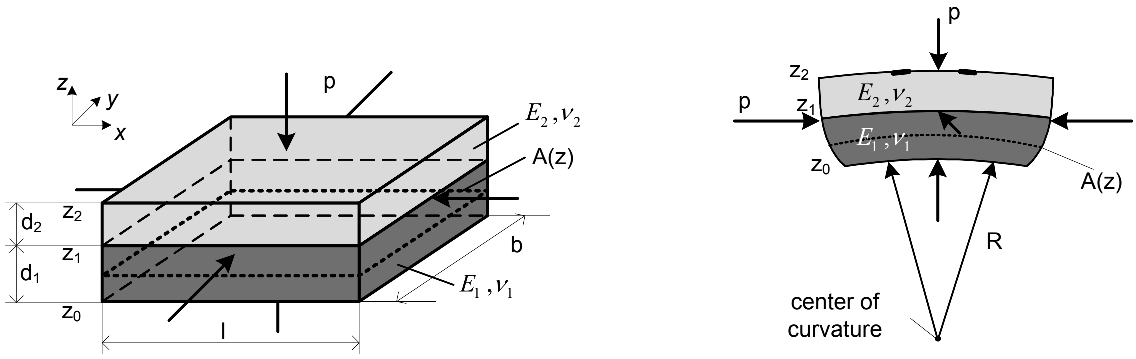


Figure 2: Model for the analytical description of the multilayered composite element

For an all-round pressurized element of volume, the mechanical stress σ_i in *i* – direction is a function of the mechanical strain ε_i and the elastic constants E_i and ν_i.

$$\sigma_i = \varepsilon_i \cdot \frac{E_i}{1-2\nu_i} \tag{1}$$

Summing up the energies of each layer results in the total potential energy *W* of a multilayered compound with *n* layers. With the simplification that the mechanical stress is only depending on the layers' thickness

(z - direction), you get the energy density $w(z)$ depending on a change of the z – coordinate. Equation (2) describes the total potential energy W by means of the continuous mechanical strain ε within the composite element.

$$W = \int w(z)\,\mathrm{d}V = \sum_{i=1}^{n} \int_{z_{i-1}}^{z_i} \left\{ \frac{\varepsilon^2(z)\cdot E_i}{2\left(1-2\nu_i\right)} \right\} \mathrm{d}A\,\mathrm{d}z \qquad (2)$$

For solving this equation it is assumed, that there is no restraint due to hydrostatic pressure. Thus the all-round pressurized composite element is at its best energetic level. That minimum of the total potential energy is a steady state of equilibrium with no external force and torque. Considering the BERNOULLI assumption of bending theory of the shell-shaped composite element, the mechanical strain within the sensing element is a function of the z – coordinate, the strain of the primary layer $\varepsilon_{z0}=\varepsilon(z_0)$ and the radius of curvature R.

$$\varepsilon(z) = \varepsilon_{z0} + \frac{1}{R}\cdot z \qquad (3)$$

The shell-shaped element aims at reaching its best energetic level. In order to get the minimum of the total potential energy, equation (2) has to be differentiated with respect to both unknown addend of equation (3), the strain of the primary layer ε_{z0} and the curvature $1/R$, and equated with zero.

$$\frac{\partial \frac{\partial W}{\partial A}}{\partial \frac{1}{R}} \overset{!}{=} 0 \quad \text{and} \quad \frac{\partial \frac{\partial W}{\partial A}}{\partial \varepsilon_{z0}} \overset{!}{=} 0 \qquad (4)$$

The minimum of total potential energy provides the radius of curvature R and mechanical stress $\sigma(z)$ of the shell-shaped element by solving the subsequent system of equations from equation (4). Hence you get the mechanical strain in dependence of the z – coordinate $\varepsilon(z)$ with equation (3).

The dissolving of the presented analytical description of the novel all-round pressurized composite element is only applied for the central axis in z – direction due to above-mentioned simplifications. Due to the not restrained surfaces, there are no bearing reactions at the edges of the composite element. Thus, the normal forces at the lateral surfaces are counteracting forces relating to the outer pressure, because of the equilibrium of forces. As a result, there is a continuous mechanical stress at the top surface of the silicon chip, where the implanted piezoresistive resistors are located. That continuous course of stress respectively strain is similar to the transmission of strain of a bonded strain gauge.

Structural analyses

Structural analysis of the composite element has also been performed using FEM-simulation software ANSYS. Thus the analytically investigated continuous mechanical stress at the top surface of the silicon chip can be presented in a simpler way. Figure 3 shows the mechanical stress along the x – respectively y – axis on top of the composite element for a hydrosatic pressure load p = 100 MPa.

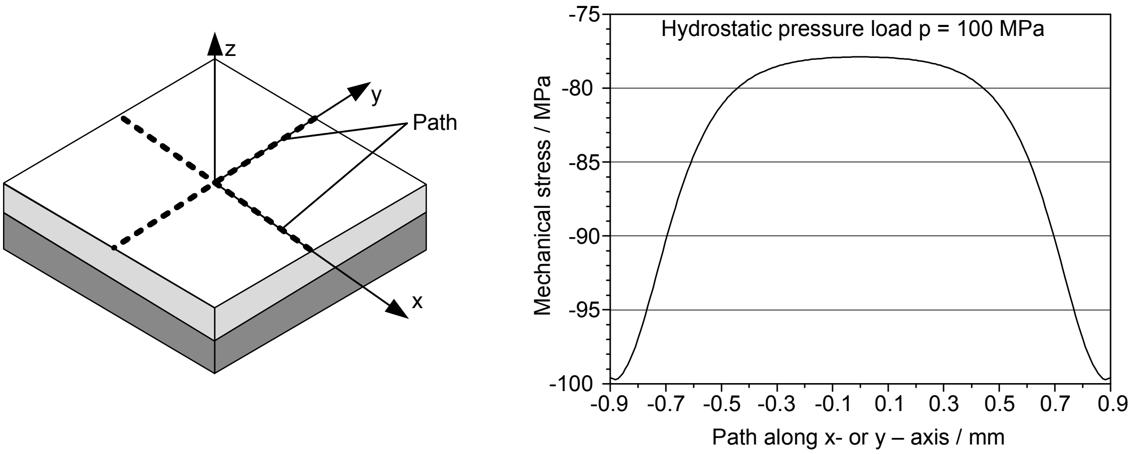


Figure 3: Mechanical stress at top of the composite element as result of structural analyses

The continuous mechanical stress on top of the silicon chip in y – direction σ_y is similar but rotated 90° in comparison to the continuous mechanical stress in x – direction σ_x. With the phenomenological description of the piezoresistive effect [5; 7], the relative change of a resistance r is directly proportional to the difference of the principal stresses.

$$r = \frac{\Delta R}{R_0} \sim \sigma_x - \sigma_y = \Delta T \tag{5}$$

Consequently, the optimized locations for the piezoresistive resistors are at the edge of the novel composite element. Of course, there have to be kept a safe margin to the elements edge. Furthermore, the physical induced dimensions of the resistors result in a non optimal resistor location at the chip.

Experimental design of novel high-pressure sensing element

The experimental design of the novel composite element consists of a state-of-the-art piezoresistive pressure sensor from the cooperator Aktiv Sensor GmbH / EPCOS AG. On the basis of the presented operation mode, there is no etched diaphragm in the solid body silicon chip, when it is anodic bonded to the solid body substrate. In order to electrically contact that composite element, there is an electrical feed through necessary to separate the high-pressure from the ambient pressure in a sealed way. The sensing element is bonded with a soft silicone adhesive to release the coupling of the mechanical stress due to the connection of the glass-to-metal-seal to the high-pressure measuring booth.

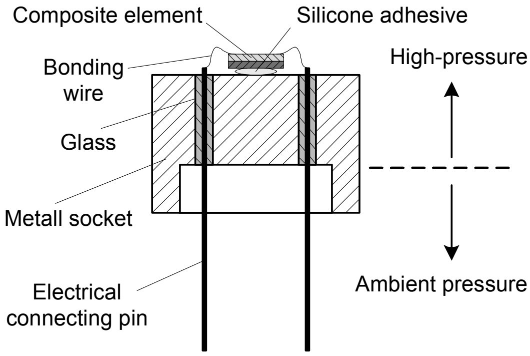
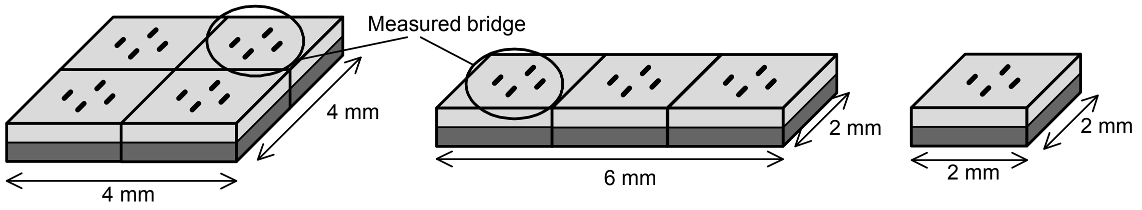


Figure 4: Cross-section of experimental design

Although the mechanical overpressure protection of the composite element itself is extremely high due to hydrostatic pressure load, the weak point of the experimental design is the electrical feed through. At the moment the measuring is realized within a pressure range up to the nominal pressure of p_n = 100 MPa only, due to the mechanical stability of used electrical feed-through.

Measurements

As well metrological and analytical investigations as finite element analysis have been done simultaneously. Thus, there have been taken measurements on different geometries of the novel composite element (Figure 5).



(a) Asymmetric element 1 *(b) Asymmetric element 2* *(c) Symmetric element*

Figure 5: Different geometries of metrological investigated composite elements

For metrological investigations there is a high-pressure measuring booth. For compression of the silicone oil as transmission medium, there is a manually driven pressing screw. It is possible to generate and verify static pressure up to 500 MPa with the Piston Gauge in a highly accurate way. For displaying lower pressure more simply, there is also a static pressure gauge up to 200 MPa connected to the high-pressure measuring booth.

First measurements have been taken from the asymmetric sensing elements (Figure 5 (a) and (b)) and have been presented in a paper [3]. Due to low sensitivity and results of the already presented analytical description and structural analyses, there have been taken measurements of symmetric composite elements (Figure 2 (c)). The piezoresistors are not located at the optimized location, due to utilizing state-of-the-art silicon pressure sensors as the experimental design of the novel high-pressure sensing element. Consequently, the margin of the symmetric sensing elements have been cut off as far as possible in means of getting a stable electrical connection and getting the resistors closer to the edge of the composite element. That improved composite element is shown in Figure 1.

A Wheatstone full-bridge circuit is integrated on top of the composite element, electrically driven by a stabilized voltage of V_s = 5 V. Various measurements with different sensing elements have been performed. The measuring is realized within a pressure range up to the nominal pressure of p_n = 100 MPa only. Figure 6 shows a representative repeatable measurement result of the improved composite element. The measurement results have been taken by two different test sequences. The

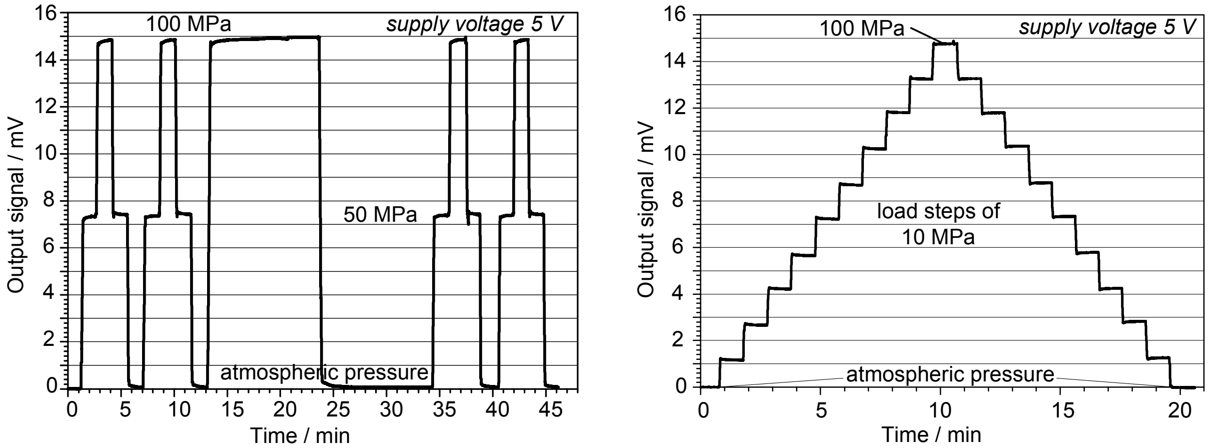


Figure 6: Repeatable measurements result of improved composite element (test sequence 1 (left) and 2 (right))

normalized sensitivity S_n (equation (6)) is calculated with the measured nominal output signal V_n = 14.8 mV at p_n = 100 MPa:

$$S_{\mathrm{n}} = \frac{V_{\mathrm{n}}}{V_{\mathrm{s}} \cdot \Delta p_{\mathrm{n}}} = 25 \frac{\mu\mathrm{V}}{\mathrm{V} \cdot \mathrm{MPa}} \qquad (6)$$

The measured characteristic curve, illustrated in Figure 7, arises from test sequence 2 of shown measurement results (Figure 6). Figure 7 illustrates that characteristic curve with actual value and desired value with fixed point adjustment. Further calculations refer to test sequence 2 for the most part.

For investigating the uncertainty of measurement, the reduced measuring errors like nonlinearity F_{nl} and hystereses error F_H are established from the measured characteristic curve. Nonlinearity and hytereses error are presented in Figure 8. That calculated uncertainty of measurement is based on test sequence 2. Here only two pressure steps are verified accurately – the atmospheric pressure $p_a \approx 0.1$ MPa and the nominal pressure p_n = 100 MPa with the piston gauge. All load steps among the two referenced are based on the reading of the static pressure gauge. Hence, the uncertainty of measurement arises from two basic reasons. On the one hand there are reading errors next to the measurement error of the static pressure gauge itself. On the other hand there is the high uncertainty of measurement of the static pressure gauge for the low pressure range till about 20 MPa especially.

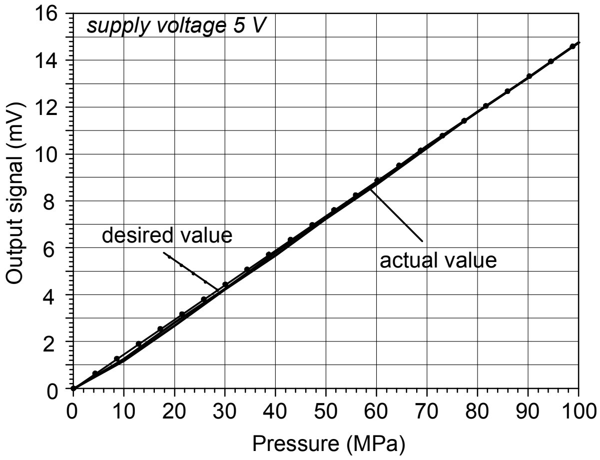


Figure 7: Measured characteristic curve of the novel composite element with actual and desired value

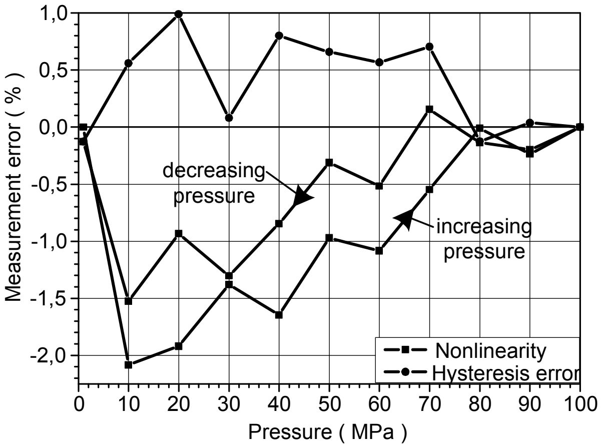


Figure 8: Nonlinearity and hysteresis error of the novel composite element

In combination with the analytical description, the improved geometry of the presented composite element (Figure 1) results in about 13 times higher output signals, compared to previously measured composite elements (Figure 5) [3]. Nonlinearity and hysteresis errors (Figure 8) as well as summarized characteristic values of shown and previously measured results are presented in Table 3.

Table 3: Comparison of measured characteristic values with hydrostatic pressure load of 100 MPa and supply voltage of 5 V

	S_n in $\frac{\mu V}{V \cdot MPa}$	F_{lin} in %	F_H in %
Asymmetric element 1	1.84	15	4.3
Asymmetric element 2	2.44	8	3.7
Symmetric Element	2.82	7.7	2.8
Improved Element	25	2.1	1.0

Table 3 shows a continuous improvement from asymmetric to symmetric and finally to the improved geometry of the measurement results. That could be seen in a way of increasing sensitivity while decreasing measurement errors occur.

Outlook

As well simulation as analytical description and measurement results yield nearly the same result. The deviations reach values smaller than one percent. Thus, the novel operating mode for measuring high-pressure values is confirmed.

The presented novel working principle of the composite element as high-pressure sensing element enables measuring high-pressure above 500 MPa due to hydrostatic pressure load, as long as the electrical connection and feed through could be improved.

The fundamentals shown in this paper enable optimization of the composite element additionally. The integrated overload protection and long-term stability represent one of the essential advantages compared to other state-of-the-art high-pressure sensors based on strain gauges. Next objective is to increase the nominal pressure with novel electrical feed-through and to design the packaging in order to protect the element against rough environment.

Acknowledgement

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