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High-pressure measurements at 500 MPa of the novel piezoresistive composite element show the influence of glass counter body

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Abstract

This paper presents initial measurement results of the novel piezoresistive composite element at 500 MPa (5 000 bar or 72 500 psi). Comparative measurements with different layer thicknesses have been carried out successfully. While the expected sensitivity improvement in dependence of the thickness-ratio is confirmed, a nonlinear characteristic of glass in combination with increasing pressure to 500 MPa and thicker glass is discovered and demonstrated.

Keywords: high-pressure; glass counter body; composite element; piezoresistive; overload protected

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1. Motivation

Applications involving high-pressure are increasingly common in engineering today; these also include mass production applications like automotive braking systems at 25 MPa, common-rail fuel injection systems at 300 MPa in research and water jet cutting or hydroforming at 600 MPa. Even higher pressure occurs for application fields in the oil, chemical and food technology with up to and even above 1 500 MPa.

State-of-the-art high-pressure sensors are commonly based on deformation bodies made of metal respectively ceramics with connected strain sensors, like metal strain gauges or metal thin film. Commonly the overload protection of these high-pressure sensors covers a range of 120% at maximum.

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Due to the monolithically deformation body these sensors are expensive in addition. Thus, there is a need for a novel overload protected and cost-effective high-pressure sensor.

2. Design of the novel silicon high-pressure sensor

The most widespread technique for measuring pressure is the piezoresistive silicon chip, due to the advantages of single-crystal sensing elements, like low-cost high-volume production, small-size, simple design, long-term stability and high sensitivity. But these piezoresistive silicon sensors cover a pressure range from 1 kPa to 100 MPa at maximum. The recently developed piezoresistive high-pressure sensing element [1, 2], named composite element, combines the advantages of silicon pressure sensors with applications in the high-pressure range. The high-pressure composite element consists of a solid silicon body connected to a mechanically mismatched counter body made of glass by anodic bonding (Fig. 1). Based on hydrostatic pressurization this high-pressure sensor design is overload protected. The resistivity change of the all-sided pressurized shell-shaped composite element is measured. Fig. 2 shows the set-up of the composite element mounted on a novel high-pressure ceramic feed-through.

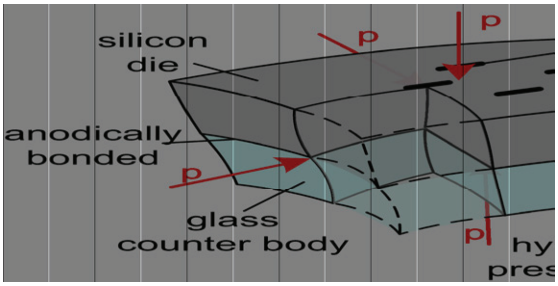

Fig. 1. Composite element; shell-shaped bent due to hydrostatic pressure load; 1.6 mm side length

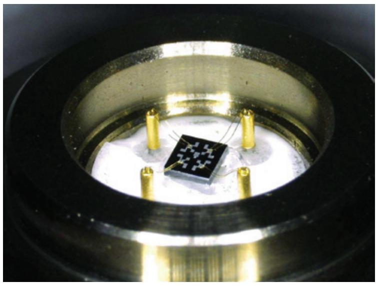

Fig. 2. Photo of composite element mounted on the novel high-pressure ceramic feed-through

3. Composite elements with different counter bodies for measuring at 500 MPa

This paper presents the first measurements of these high-pressure composite elements for the intended nominal pressure range from 100 MPa to 500 MPa (5 000 bar or 72 500 psi). Table 1 shows the thickness ratio of the measured composite elements at 500 MPa. Because the glass thickness of element 1 is chosen more than twice as thick as the silicon, the influence of high-pressure on glass is analyzed. On basis of [3], the ratio of the layers' thickness is not adapted, thus the sensitivity does not reach its possible maximum for the current design of the composite element.

Table 1. Layer thickness of the two composite elements

Thickness of		Element 1	Element 2
Silicon die	µm	390	390
Glass counter body	µm	850	480
Thickness-ratio (glass / silicon)		2.18	1.23

4. Measurement results show the pressure dependent influence of glass thickness

The characteristic values are calculated individually for several measurements at load cycles with stepwise increasing nominal pressure up to 500 MPa. Fig. 3 shows a representative measurement with a load cycle at 500 MPa of element 1. Evaluating the measurement results of element 1 with a glass counter body more than twice as thick as the silicon die - shown in table 2 - the normalized sensitivity increases with higher pressure-load by 8% in comparison of 100 MPa to 500 MPa. This increasing sensitivity as well as the increasing nonlinearity on higher pressure is presented in Fig. 4. There is no influence of increasing pressure on the hysteresis error or the zero point error.

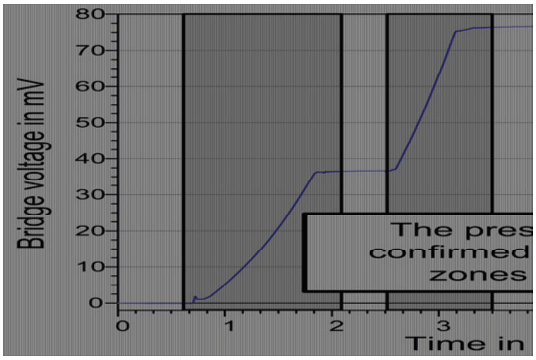

Fig. 3. Representative measurement of element 1 at nominal pressure of 500 MPa; 2.5 V supply; room temperature at 22°C ± 2°C

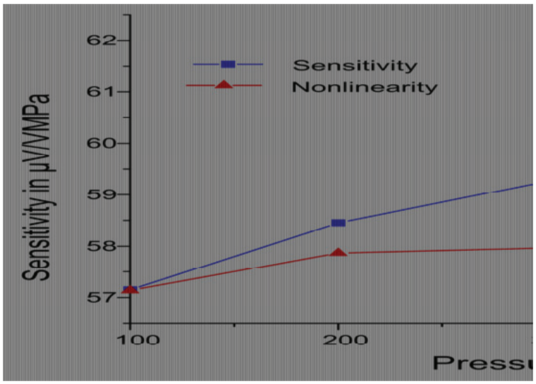

Fig. 4. Plot of the normalized sensitivity and the nonlinearity of element 1 over the nominal pressure (Table 2)

Table 2. Characteristic values of element 1 at different nominal pressures

Nominal pressure	MPa	100	200	300	400	500
Nominal output signal	mV	14.29	29.22	44.44	60.92	77.14
Sensitivity	µV/VMPa	57.15	58.45	59.26	60.92	61.72
Nonlinearity	%	0.53	1.14	1.22	1.69	2.11
Hysteresis error	%	0.20	0.29	0.19	0.18	0.16
Zero point error	%	0.07	0.35	0.04	0.18	0.03

The individually evaluated characteristic values are compared for the two composite elements with different silicon to glass thickness-ratio (Table 1). Fig. 5 shows the representative measurement of element 2 with a thickness-ratio closer to 1 at 500 MPa. Evaluating the characteristic values of element 2, shown in table 3, the sensitivity increases only by 1.5% with increasing nominal pressure (Fig. 6). In comparison to element 1, the nonlinearity of element 2 shows no influence on increasing pressure.

Therefore, the deviation of sensitivity as well as the nonlinearity is much smaller for element 2 than for element 1. The larger deviation and nonlinearity of element 1 is due to the thicker glass counter body. Because of the constant silicon thickness, the retroactive effect of the nonlinear behavior of glass as result of high pressure increases with higher thickness-ratio of glass to silicon.

The expected improvement of sensitivity in dependence on the thickness-ratio, like presented in [3], shows the comparison of both elements (table 2 and 3). However, it is striking that there are deviations

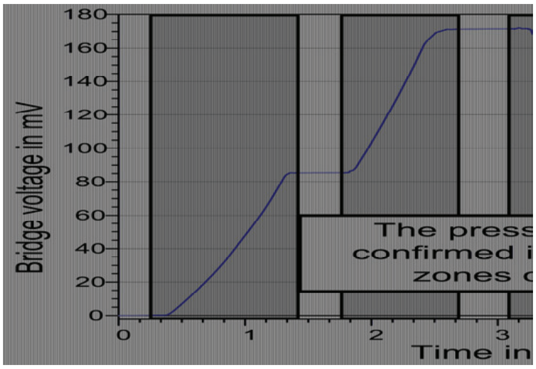

Fig. 5. Representative measurement of element 2 at nominal pressure of 500 MPa; 2.5 V supply; room temperature at 22°C ± 2°C

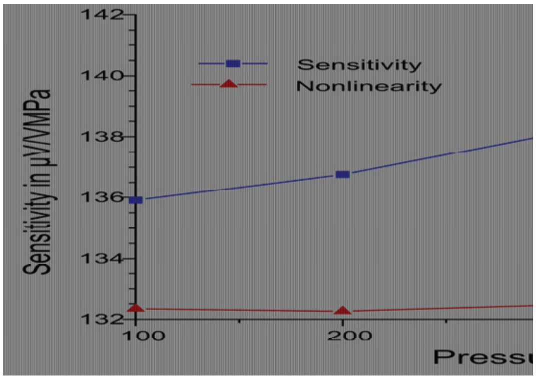

Fig. 6. Plot of the normalized sensitivity and the nonlinearity of element 1 over the nominal pressure (Table 2)

for a thickness-ratio larger than 1.25 from the presented approach in [3], due to increasing nonlinear behavior of glass as influence of high pressure loading.

Table 3. Characteristic values of element 2 at different nominal pressures

Nominal pressure	MPa	100	200	300	400	500
Nominal output signal	mV	33.98	68.38	103.5	137.2	172.5
Sensitivity	µV/VMPa	135.9	136.8	138.1	137.2	138.0
Nonlinearity	%	0.17	0.13	0.23	0.12	0.26
Hysteresis error	%	0.08	0.02	0.10	0.08	0.29
Zero point error	%	0.65	0.20	0.26	0.07	0.01

5. Conclusion

With shown results, the deviation from the presented approach in [3] is about 10% for the thickness-ratio of 2.18, while the deviations for thickness-ratio smaller 1.25 is smaller than 1.5%. With that demonstrated nonlinear characteristic of thicker glass and the thickness-ratio approach of [3], the optimal thickness-ratio for best performance and highest sensitivity is about 0.6 for measuring high-pressure with the novel piezoresistive composite element.

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