

# TEMPERATURE BEHAVIOUR OF CAPACITIVE PRESSURE SENSOR FABRICATED WITH LTCC TECHNOLOGY

Darko Belavič, Marina Santo Zarnik, Marko Hrovat\*,  
Srečko Maček\*, Marija Kosec\*

HIPOT-RR d.o.o., 8310 Šentjernej, Slovenia  
\*Jožef Stefan Institute, 1000 Ljubljana, Slovenia

**Key words:** sensor, pressure sensor, capacitive pressure sensor, thick-film technology, temperature behaviour

**Abstract:** This work is focused on capacitive pressure sensors designed as ceramic capsules, made with low-temperature cofired ceramic (LTCC), consisting of a circular edge-clamped deformable diaphragm that is bonded to a rigid ring and the base substrate. This construction forms the cavity of the pressure sensor. The diaphragm, with a diameter of 9.0 mm has a thickness of 200  $\mu\text{m}$ , and the depth of the cavity is from about 70  $\mu\text{m}$ . The principle of capacitive pressure sensor is based on changes of the capacitance values between two electrodes. One thick-film electrode is deposited on the diaphragm and the other on the rigid substrate. The distance between electrodes and the area of electrodes define the initial capacitance of the capacitive pressure sensor, which is around 10 pF. The distance between electrodes and together with the geometry and flexibility of the diaphragm define the sensitivity of the sensor, which is about 4 fF/kPa. We investigated the temperature dependence of the sensors' characteristics of capacitive thick-film pressure sensors. The sensor is based on changes the capacitance values between two electrodes: one electrode is fixed and the other is movable. The displacement of the movable electrode depends on the applied pressure. The main influence on the temperature dependence of the sensor characteristics is from the temperature coefficient of the elasticity and sensor's geometry, while the temperature coefficient of the Poisson's ratio and the temperature expansion coefficient have only a minor effect.

## Temperaturne lastnosti kapacitivnega senzorja tlaka narejenega v LTCC tehnologiji

**Ključne besede:** senzor, senzor tlaka, kapacitivni senzor tlaka, debeloplastna tehnologija, temperaturna odvisnost

**Izveček:** V prispevku so prikazani raziskovalni rezultati na kapacitivnem senzorju tlaka narejenemu v LTCC tehnologiji. LTCC (Low Temperature Cofired Ceramic) je keramika z nizko temperaturo žganja. Ta keramika se žge pri temperaturah med 850 in 950°C. Da se pri teh razmeroma nizkih temperaturah zasnira, vsebuje precej steklene faze. LTCC tehnologija temelji na tankih keramičnih folijah, ki se jih sestavlja v večplastne strukture. Na ta način je možno zgraditi tridimenzionalno strukturo za kapacitivni senzor tlaka. Osnovo take strukture predstavlja tanka okrogla in upogljiva membrana. Rob membrane je pritrjen na obroč, ta pa na trdo (neupogljivo) podlago. Ena elektroda kondenzatorja je na membrani, druga pa na podlagi. Merjeni tlak upogne membrano, kar spremeni razdaljo med elektrodama. S tem dobimo spremembo kapacitivnosti. Senzor tlaka za tlačno področje do 100 kPa ima membrano s premerom 9,0 mm in debelino 200  $\mu\text{m}$ . Pri razmaku med elektrodama okoli 70  $\mu\text{m}$  je začetna kapacitivnost približno 10 pF. Razmak med elektrodama ter geometrija in fleksibilnost membrane določata občutljivost senzorja na merjeni tlak. Raziskovali smo temperaturno odvisnost karakteristik kapacitivnega senzorja tlaka. Na njo v glavnem vpliva temperaturna odvisnost modula elastičnosti LTCC materiala, delno pa tudi temperaturni razteznostni koeficient LTCC materiala ter konstrukcija in dimenzije tridimenzionalne LTCC strukture. Na temperaturno odvisnost začetne kapacitivnosti pa je znatno vplivajo zaostale mehanske napetosti v membrani in eventualna predhodna ukrivljenost membrane.

### 1 Introduction

Pressure is a mechanical quantity defined as the ratio of force to the surface area over which it is exerted. A complete pressure-measurement system consists of a series of components. One of them is the sensing element (a transducer) that responds to the pressure applied to it and converts the pressure into a measurable signal, which in most cases is an electrical signal. In most cases the sensing elements in pressure sensors are based on strain-gauge, capacitive, piezoelectric or optical principles to convert the physical quantity (pressure) into an electrical signal. The majority of pressure sensors on the market is based on piezoresistive principle. This is mainly due to the fact that the piezoresistive pressure sensors are relatively sensitive to an applied pressure and their analogue output is linear in a wide pressure range while the output impedance is low. For capacitive pressure sensors the

pressure sensitivity is essentially higher than that of piezoresistive pressure sensors, and the power consumption is much lower. The major disadvantages are their small sensing capacitance, high output impedance and nonlinearity of the sensors response. The small capacitance makes them highly susceptible to parasitic effects.

Most pressure sensors are made by micro-machining silicon /1,2/. On the other hand, complex sensor systems combine different materials (silicon, ceramic, metal, polymer, etc.) and technologies (semiconductor, thin and thick film, etc.). In some demanding applications thick-film technology and ceramic materials are a very useful alternative /3-6/. In many cases low-temperature cofired ceramic (LTCC) is used for the fabrication of thick-film pressure sensors. In comparison with semiconductor sensors they are larger, more robust and have a lower sensitivity, but they operate over a wider operating-temperature range /3,5/.

This contribution includes the study of sensing principle, investigated materials, and designing a capacitive pressure sensor using thick-film and LTCC materials and technology. The special attention is focused on the temperature dependence of sensor's characteristics

## 2 LTCC materials

The low-temperature cofired ceramic (LTCC) technology is a rapidly growing segment of the hybrid electronic-module market. The LTCC technology is a three-dimensional ceramic technology utilizing the third dimension (z) for the interconnects-layers, the electronic components, and the different three-dimensional (3D) structures, such as cantilevers, bridges, diaphragms, channels and cavities. It is a mixture of thick-film and ceramic technologies. Thick-film technology contributes the lateral and vertical electrical interconnections, and the embedded and surface passive electronic components (resistors, thermistors, inductors, capacitors). Ceramic technology contributes the electrical, mechanical and dielectric properties as well as different 3D structures /6,7/.

LTCC materials in the green state (called green tapes, before sintering) are soft, flexible, and easily handled and mechanically shaped. A large number of layers can be laminated to form high-density interconnections and three-dimensional structures. The fabrication process of LTCC structures includes several steps, which are named LTCC technology. The separate layers are the mechanical shaping of meso-size features (0.1-15 mm), and then the thick-film layers are the screen-printed. All the layers are then stacked and laminated together with hot pressing. This laminates are sintered in a one-step process (cofiring) at relatively low temperatures (850–900°C) to form a rigid monolithic ceramic multilayer circuit (module). Some thick-film materials need to be post-fired; thick-film pastes are screen-printed on the pre-fired laminate and have to be fired again. The whole LTCC process saves time, money and reduces the circuit's dimensions compared with conventional hybrid thick-film technology.

The important advantage for pressure sensors applications is the lower Young's modulus (about 100 GPa) of LTCC materials in comparison with alumina (about 340 GPa). As example Figure 1 shows the comparison of deflections of the diaphragms made with alumina and LTCC materials. The calculated deflections as a function of the distance from the diaphragm centre (r) are presented for the pressure sensors with the same dimensions at an applied pressure of 100 kPa. The diameter of the circular edge-clamped diaphragm is 9.0 mm, and the thickness is 200µm. The biggest deflection, of 8.5 µm in the middle of the circular diaphragm, was observed for the LTCC, and the lowest deflection, of 2.7 µm, was exhibited by the alumina diaphragm.

The LTCC tapes consist of ceramic and glass particles suspended in an organic binder. The materials are either

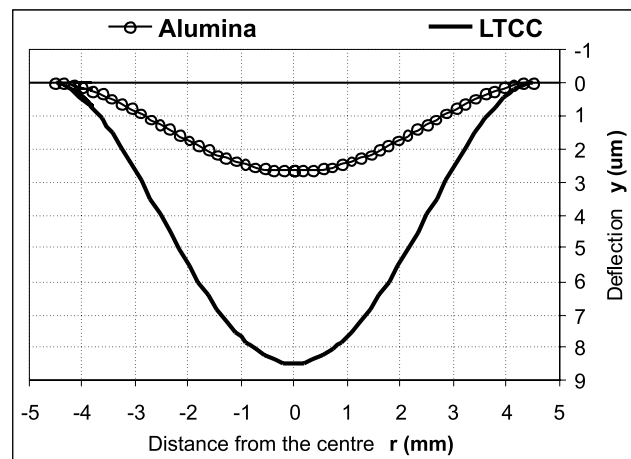


Fig.1: The calculated deflections of diaphragms made with alumina and LTCC materials at an applied pressure of 100 kPa.

based on crystallisable glass or a mixture of glass and ceramics, for example, alumina, silica or cordierite ( $Mg_2Al_4Si_5O_{18}$ ) /8/. The composition of the inorganic phases in most LTCC tapes is similar to, or the same as, materials in thick-film multilayer dielectric pastes. To sinter to a dense and non-porous structure at these, rather low, temperatures, it has to contain some low-melting-point glass phase. This glass could presumably interact with other thick-film materials, leading to changes in the electrical characteristics /8,9/. The composition of a typical LTCC material is shown in Figure 2.

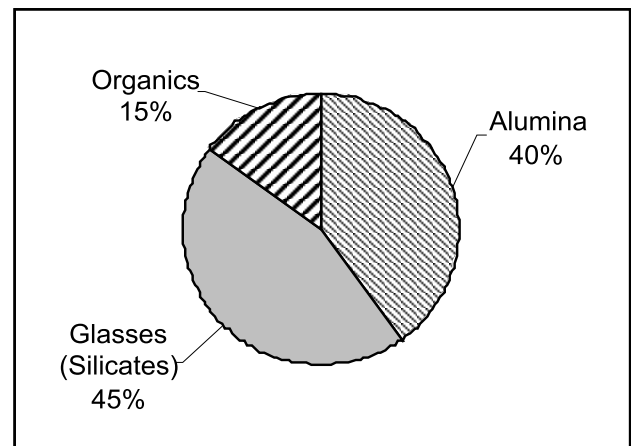


Fig.2: The composition of a typical green LTCC material (wt.%).

The disadvantages of LTCC technology as compared with an alumina are a lower thermal conductivity (about 2.5 to 4 W/mK) in comparison with alumina and the shrinking (about 10 to 15% in x/y-axis and about 10 to 45% in z-axis) of the tapes during firing. Some of the characteristics of alumina substrates and fired LTCC laminates are presented in Table 1.

Table 1: Some characteristics of LTCC material in comparison with  $Al_2O_3$  ceramics

Characteristics	$Al_2O_3$ (94-99.5%)	LTCC
Thermal expansion coeff. ( $10^{-6}/K$ )	7.6-8.3	5.8-7.0
Density ( $g/cm^3$ )	3.7-3.9	2.5-3.2
Flexural strength (MPa)	300-460	170-320
Young's modulus (GPa)	215-415	90-110
Thermal conductivity ( $Wm/K$ )	20-26	2.0-4.5
Dielectric constant	9.2-9.8	7.5-8.0
Loss tg ( $\times 10^{-3}$ )	0.5	1.5-2.0
Resistivity (ohm.cm)	$10^{12}-10^{14}$	$10^{12}-10^{14}$
Breakdown (V/100 $\mu m$ )	3000-4000	>4000

### 3 LTCC Structure

Most ceramic pressure sensors are made with deformable diaphragms /5/. The deformation is induced by the applied pressure and then converted into an electrical signal. LTCC technology and materials are suitable for forming a three-dimensional (3D) construction, consisting of a circular edge-clamped deformable diaphragm that is bonded to a rigid ring and a base substrate /3,6,7/. These elements form the cavity of the pressure sensor. The cross-section of ceramic pressure sensor is shown in Figures 3 and 4.

Cross-section (not to scale)

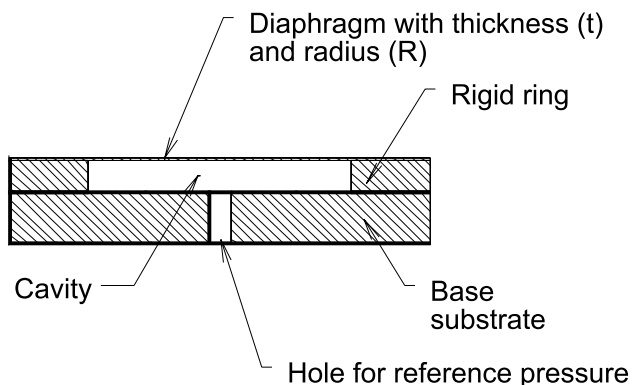


Fig.3: The schematic cross-section of the LTCC structure of a pressure sensor (not to scale).

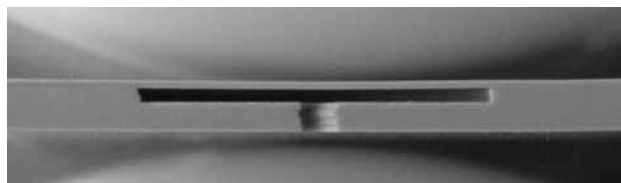


Fig.4: The cross-section of 3D LTCC structure for the pressure sensor.

### 4 LTCC Capacitive Pressure SENSOR

The LTCC capacitive pressure sensor is based on the fractional change in capacitance (DC/C) induced by the applied pressure. The capacitance change can be due to changes of the distance between the electrodes of the capacitor, to changes of the permittivity of the dielectric materials, or changing both. In this contribution we present the capacitive pressure sensor based on changes of the distance between the electrodes of the air capacitor.

The construction of the thick-film capacitive sensor is very similar to other thick-film pressure sensors /10-13/. The difference is that the distance between the deformable diaphragm and the rigid base substrate is smaller and must be very well defined. The bottom electrode of the capacitor is on the rigid substrate and the upper electrode is on the deformable diaphragm. Therefore, the area of the electrode and the distance between them define the value of the initial capacitance of the pressure sensor. The principle of the construction is shown in Figure 5.

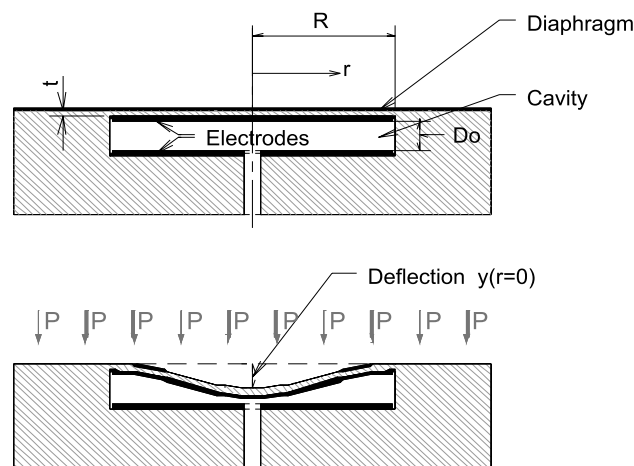


Fig.5: The cross-section of a capacitive pressure sensor without (above) and with (bottom) applied measuring pressure (schematic, not to scale).

The capacitive pressure sensors' characteristics depend on the construction, the dimensions and the material properties (Table 1) of the sensor body and sensing capacitor /10-15/. The influence of the geometry and the material properties of the LTCC structure on the deflection of an edge-clamped deformable diaphragm under an applied pressure is described by equation (1)

$$y(r) = \frac{3P(1-\nu^2)(R^2 - r^2)^2}{16Et^3} \tag{1}$$

where the deflection  $y$  at the position  $r$  from the centre of the diaphragm is a function of the applied pressure,  $P$ , the material characteristics (elasticity,  $E$ , and Poisson's ratio,  $\nu$ ) of the diaphragm, and the dimensions (thickness,  $t$ , and radius,  $R$ ) of the diaphragm (Figures 3 and 5).

The value of initial capacitance ( $C_0$ ) of the capacitive pressure sensor is defined with the areas of the electrodes and the distance between them. The distance between the electrodes ( $D$ ) is subtracted from cavity depth and the thickness of both electrodes. When the deflection of the diaphragm  $y(r=0)$  under an applied pressure is much smaller than the thickness of the diaphragm and the separation of the electrodes than the capacitance between electrodes is given by equation (2)

$$C(P) = \epsilon_0 \cdot \epsilon_r \cdot \int_0^R \frac{2 \cdot \pi \cdot r \cdot dr}{D_0 - y(r)} \tag{2}$$

where  $C$  is the capacitance under an applied pressure  $P$ ,  $\epsilon_0$  is the permittivity in vacuum,  $\epsilon_r$  is the relative permittivity,  $R$  is the radius of the electrode,  $r$  is the current radius,  $D_0$  is the distance between the electrodes at zero applied pressure and  $y(r)$  is the deflection at the current radius  $r$  when the pressure  $P$  is applied.

The air capacitor of the test samples of the LTCC capacitive pressure sensor was designed as a cavity with a diameter of 9.0 mm and a height of about 80  $\mu\text{m}$ . The thickness of the diaphragm is 200  $\mu\text{m}$ , and the dimensions of the whole LTCC structure are 18.0  $\times$  12.5  $\times$  1.4 mm. The diameter of the upper and bottom electrodes is 8.6 mm. The test samples of the sensors were fabricated with LTCC materials Du Pont 951. The diaphragm has a thickness of 200  $\mu\text{m}$ . The fabricated samples, which are shown in Figure 6, were tested in the range from 0 to 70 kPa, where the sensor's response is linear. The test samples were measured at five different temperatures (-25°C, 0°C, 25°C, 50°C and 75°C).

### 5 Results and discussion

All the test samples were tested at different applied pressures and at different temperatures. The initial capacitances ( $C_0$ ) of the pressure sensors are between 8 and 10 pF. The relative changes in the initial capacitance of the pressure sensors M2/1 and M3/1) versus the different temperatures are shown in Figures 7 and 8. The calculate temperature coefficients of initial capacitances for two samples M2/1 and M3/1 calculated from experimental results presented in Figures 7 and 8 are about  $-350 \times 10^{-6}/\text{K}$  and  $+300 \times 10^{-6}/\text{K}$  respectively. Those selected test samples have extreme values (maximum and minimum) of temperature coefficients of initial capacitances. Other fabricated samples have lower values and mostly located in two

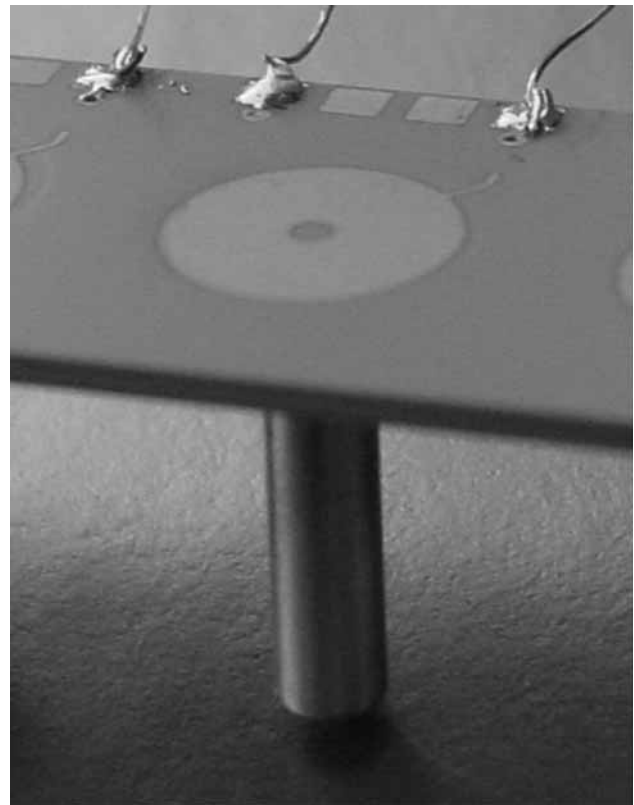


Fig.6: The capacitive pressure sensors made in a 3D LTCC structure.

groups. The first group has average value about  $-250 \times 10^{-6}/\text{K}$  and the second about  $+200 \times 10^{-6}/\text{K}$ .

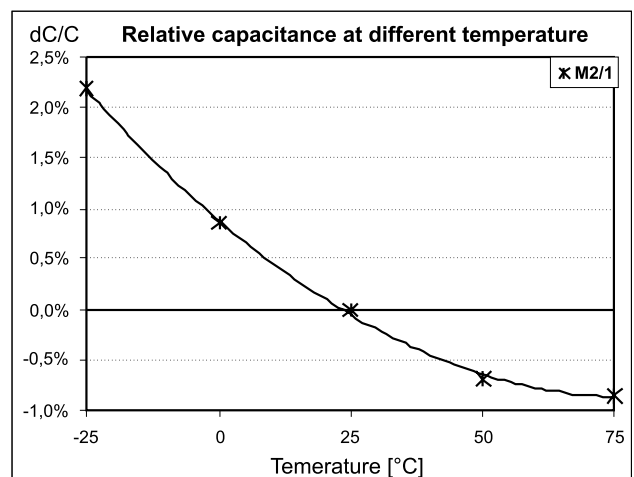


Fig.7: The relative change of initial capacitance at different temperatures for the capacitive pressure sensor M2/1.

The capacitance of the pressure sensors versus negative applied pressure is shown in Figure 9 and the calculated pressure sensitivities from the measured data are between 3.5 and 5.0 fF/kPa. The temperature dependences of sensitivity are not linear and relative high from  $-700$  to  $2000 \times 10^{-6}/\text{K}$ .

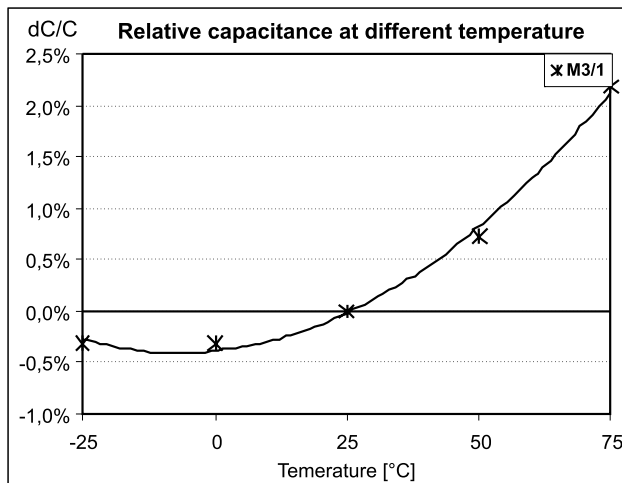


Fig.8: The relative change of initial capacitance at different temperatures for the capacitive pressure sensor M3/1.

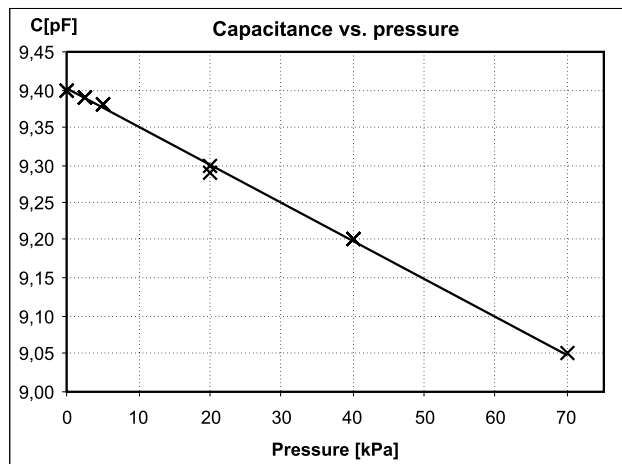


Fig.9: The capacitance versus the negative applied pressure of the capacitive pressure sensor.

The temperature has a noticeable influence on the material characteristics (elasticity and Poisson's ratio) and the fractional changes in the dimensions /8/. The data on the temperature dependence of elasticity of LTCC materials are not available. For this study we presumed that the values of the temperature coefficients of elasticity (TCE) of the LTCC are between the TCE of alumina and the TCE of glass. Therefore, we used a value of  $-250 \times 10^{-6}/K$  in our calculations. The data on temperature dependence of the Poisson's ratio of LTCC materials is also not available. The temperature dependence of the Poisson's ratio of alumina is  $68 \times 10^{-6}/K$ . Therefore,  $100 \times 10^{-6}/K$  was used as a rough estimation for the temperature coefficient of the Poisson's ratio of the glassy-alumina-filled LTCC material. The temperature expansion coefficient (TEC) of LTCC materials is  $5.8 \times 10^{-6}/K$ .

Some analytically calculated and experimental values of the characteristics of the LTCC capacitive pressure sensor are presented in Table 2. The main influence on the temperature dependence of the sensor characteristics is from the temperature coefficient of the elasticity, while the

temperature coefficient of the Poisson's ratio and the temperature expansion coefficient have only a minor, and opposite, effect on the temperature coefficient of capacitance and the temperature coefficient of sensitivity.

Table 2: Analytically calculated and experimental values of the characteristics of the LTCC capacitive pressure sensor

Characteristics	Calculated Value	Experimental Value
Initial capacitance (pF)	8.7	8÷10
Sensitivity (fF/kPa)	4.0	3.5÷5.0
Temperature coefficient of initial capacitance ( $\times 10^{-6}/K$ )	5.3	-200÷300
Temperature coefficient of sensitivity ( $\times 10^{-6}/K$ )	260	700÷2000

We presume that the significant differences between the experimental and the analytical results of temperature dependences of sensors characteristics lies in the residual stresses and diaphragm pre-bending. Those two effects are not included into the analytical analyses although they have significant influence on the temperature dependences of sensors characteristics. This defectiveness can be corrected by electronic conditioning circuit. For this reason we made the capacitive pressure sensor as the part of the electronic conditioning circuit with the frequency output. The typical output frequency is between 10 and 14 kHz, and depends on the applied pressure. The output frequency versus applied pressure is shown in Figure 10. The calculated pressure sensitivities from the measured data are between 2.5 and 3.5 Hz/kPa. The relative output frequency versus applied pressure at different temperatures is shown in Figure 11. The temperature dependence of initial frequency is relatively high and must be compensated, while the temperature dependence of sensitivity is from  $-200$  to  $350 \times 10^{-6}/K$ .

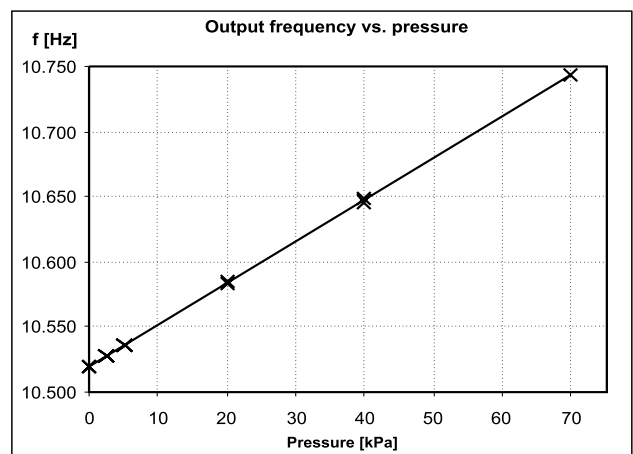


Fig.10: The output frequency versus the applied pressure of the capacitive pressure sensor with the electronic conditioning circuit.

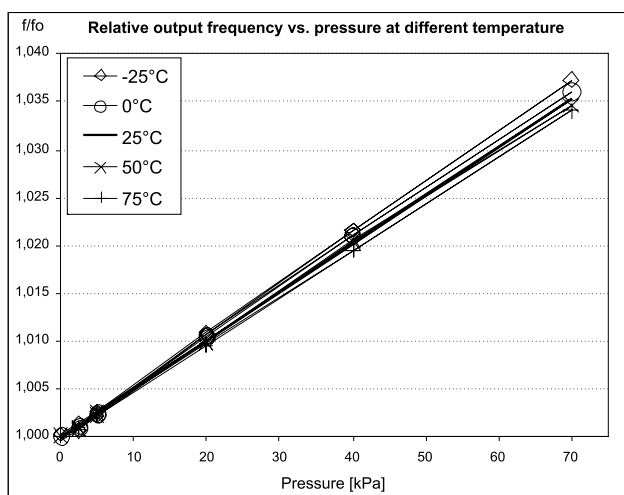


Fig.11: The relative output frequency at different temperatures versus the applied pressure of the capacitive pressure sensor with the electronic conditioning circuit.

## Conclusion

The fabrication of capacitive pressure sensors using thick-film and LTCC materials and technology is challenging opportunity for pressure sensors market. The applied pressures generate a relatively small deflection of ceramic diaphragm. This is suitable to use in capacitive pressure sensor because it means that the response of sensors is usefully linear. However, special attention during the fabrication process must be paid to the parallelism of the capacitor electrodes and the repeatability of capacitor dimensions' (areas of electrodes and s distance between them). For the use in the wide temperature ranges the temperature dependences of the sensors characteristics must be compensated by the electronic circuits. The electronic circuits must be used also to minimize the problem of very high output impedance of the pressure sensor. The output capacitance is small, of the order of a few 10 pF, and the changes in this capacitance are of the order of a few fF. This makes it very susceptible to parasitic effects. For capacitive measuring circuits, it is therefore important to minimize the physical separation between the sensing element, i.e. capacitor, and the rest of the circuit.

## Acknowledgements

The financial support of the Slovenian Research Agency and the company HYB d.o.o. in the frame of the project L2-7073 is gratefully acknowledged.

The authors wish to thank Mr. Mitja Jerlah (HIPOT-RR) for fabricate test samples.

The paper is dedicated to Professor Lojze Trontelj, Faculty of Electrical Engineering, University of Ljubljana, because of his outstanding and significant contribution in the field of microelectronics and electronic components in Slovenia.

## References

- /1/ N. M. White, J. D. Turner, "Thick film sensors: past, present and future", *Measurements. Sci. Technol.*, Vol. 8, No. 1, pp. 1-20, 1997.
- /2/ M. Pavlin, D. Belavič, M. Santo Zarnik, M. Hrovat, M. Možek, "Packaging technologies for pressure-sensors". *Microelectronics International*, Vol. 19, pp. 9-13, 2002.
- /3/ T. Thelemann, H. Thust, M. Hintz, "Using LTCC for microsystems", *Microelectronics International*, Vol. 19, No. 3, pp. 19-23, 2002.
- /4/ M. Pavlin, F. Novak, "Yield enhancement of piezoresistive pressure sensors for automotive applications", *Sensors and Actuators, A, Physical*, Vol. 141, No. 1, pp. 34-42, January 2007.
- /5/ D. Belavič, M. Hrovat, M. Pavlin, M. Santo Zarnik, "Thick-film technology for Sensor Applications", *Informacije MIDEM*, Vol. 33, pp. 45-48, 2003.
- /6/ L.J. Golonka, A. Dziedzic, J. Kita, T. Zawada, "LTCC in microsystem application", *Informacije MIDEM*, Vol. 32, No.4, pp. 272-279, December 2002.
- /7/ T. Thelemann, H. Thust, M. Hintz, "Using LTCC for Microsystems", *Microelectronics International*, Vol. 19, pp. 19-23, 2002.
- /8/ C.J.Ting, C.S. Hsi, H.J. Lu, "Interactions between ruthenium-based resistors and cordierite-glass substrates in low temperature co-fired ceramics", *Journal of the American Ceramics Society*, Vol. 83, pp. 23945-2953, 2000.
- /9/ A.A. Shapiro, D.F. Elwell, P. Imamura, M.L. McCartney, "Structure-property relationships in low-temperature cofired ceramic", *Proceedings of the 1994 International Symposium on Microelectronics ISHM-94*, Boston, Massachusetts, pp. 306-311, 1994.
- /10/ R. Puers, "Capacitive sensors; when and how to use them", *Sensors and Actuators A*, Vol. 37, pp. 93-105, 1993R. Puers, "Capacitive sensors; when and how to use them", *Sensors and Actuators A*, Vol. 37, pp. 93-105, 1993.
- /11/ C. B. Sippola, C. H. Ahn, "A thick film screen-printed ceramic capacitive pressure microsensor for high temperature applications", *Journal of Micromechanics and Microengineering*, Vol.16, pp. 1086-1091, 2006.
- /12/ J.I. Pavlič, M. Santo Zarnik, D. Belavič, "Feasibility study of a ceramic capacitive pressure sensor", *Proceedings. Ljubljana: MIDEM - Society for Microelectronics, Electronic Components and Materials*, pp. 95-100, 2006.
- /13/ M. Yamada, T. Takebayashi, S. I. Notoyama, K. Watanabe, "A Switched-Capacitor Interface for Capacitive Pressure Sensors", *IEEE Transactions on Instrumentation and Measurement*, Vol. 41, No. 1, pp. 81-86, February 1992.
- /14/ D. Belavič, M. Santo Zarnik, M. Jerlah, M. Pavlin, M. Hrovat, S. Maček, "Capacitive thick-film pressure sensor: material and construction investigation", *Proceedings of the XXXI International Conference of IMAPS Poland 2007*, Rzeszów, Krasicyzn, Poland, pp. 249-253, September 23-26, 2007.
- /15/ D Crescini, V Ferrari, D Marioli and A Taroni, "A thick-film capacitive pressure sensor with improved linearity due to electrode-shaping and frequency conversion", *Meas. Sci. Technol.* Vol. 8, pp. 71-77, 1997.

Darko Belavič, univ.dipl.eng.el.  
HIPOT-RR d.o.o.  
c/o Jožef Stefan Institute  
Jamova 39, 1000 Ljubljana, Slovenia

Phone: +386 1 4773 479  
E-mail: darko.belavič@ijs.si