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CONSTRUCTION OF A PIEZOELECTRIC-BASED RESONANCE CERAMIC PRESSURE SENSOR DESIGNED FOR HIGH-TEMPERATURE APPLICATIONS

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Abstract

In this work the design aspects of a piezoelectric-based resonance ceramic pressure sensor made using low-temperature co-fired ceramic (LTCC) technology and designed for high-temperature applications is presented. The basic pressure-sensor structure consists of a circular, edge-clamped, deformable diaphragm that is bonded to a ring, which is part of the rigid ceramic structure. The resonance pressure sensor has an additional element – a piezoelectric actuator – for stimulating oscillation of the diaphragm in the resonance-frequency mode. The natural resonance frequency is dependent on the diaphragm construction (*i.e.*, its materials and geometry) and on the actuator. This resonance frequency then changes due to the static deflection of the diaphragm caused by the applied pressure. The frequency shift is used as the output signal of the piezoelectric resonance pressure sensor and makes it possible to measure the static pressure. The characteristics of the pressure sensor also depend on the temperature, *i.e.*, the temperature affects both the ceramic structure (its material and geometry) and the properties of the actuator. This work is focused on the ceramic structure, while the actuator will be investigated later.

Keywords: LTCC, piezoelectric, pressure sensor.

1. Introduction

Pressure sensors convert the physical quantity of pressure into an electrical signal. A noticeable trend in the market for pressure sensors is an increasing need for sensors that operate over extended temperature ranges with a maximum temperature of 150°C – and even up to 250°C. Most pressure sensors are made using the semiconductor technology and the micro-machining technology of silicon, while ceramic pressure sensors, in comparison with semiconductor sensors, are larger, more robust and are capable of operating at higher temperatures. Typical ceramic pressure sensors contain a deformable diaphragm. The deformation of the diaphragm is induced by the applied pressure and then converted into an electrical signal. In most cases the sensing elements of ceramic pressure sensors are based on piezo-resistive properties of thick-film resistors that are screen-printed and fired on a deformable diaphragm. In some applications, capacitive pressure sensors, based on fractional changes in capacitance induced by the applied pressure, and piezoelectric resonance pressure sensors, based on the piezoelectric properties of a piezoelectric device that acts as an actuator/sensor on a deformable diaphragm, are useful alternatives [1−7].

The low-temperature co-fired ceramic (LTCC) technology is a three-dimensional ceramic technology for interconnection of layers and electronic components. The main advantage is its compatibility with thick-film technologies, which are used for the lateral and vertical electrical interconnections, and the embedded and surface passive electronic components (resistors, thermistors, inductors and capacitors). Electronic devices and systems based on a combination

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of the LTCC and thick-film technologies are reliable and their characteristics are stable [8−11]. With a nonconventional application of the LTCC technology a ceramic pressure sensor with a deformable diaphragm can be realised. In comparison with a conventional (alumina-based) ceramic pressure sensor, the LTCC pressure sensor has approximately three times higher pressure sensitivity and provides more flexibility in terms of design and construction. For this reason, the number of pressure-sensor applications involving the LTCC technology is growing. [8−10].

In this contribution we present the design aspects of construction of a piezoelectric-based resonance ceramic pressure sensor made using the LTCC technology and a piezoelectric actuator for stimulating oscillation of the diaphragm. The sensor's characteristics were studied for the operating-temperature range between 25°C and 250°C. The main construction parameters affecting the temperature behaviour of the sensor were identified.

2. Design and construction

Most ceramic pressure sensors are made with deformable diaphragms. Deformation of a diaphragm is induced by applying a static pressure to the sensor, which is then converted into an electrical signal by changing one of the characteristics of thick-film electronic components or structures. The three-dimensional construction of a pressure sensor consists of a circular, edge-clamped, deformable diaphragm bonded onto a rigid ring, and the base substrate. These elements form a cavity, which is used to create the pressure in the sensor. The cross-section of this type of ceramic pressure sensor is schematically shown in Fig. 1.

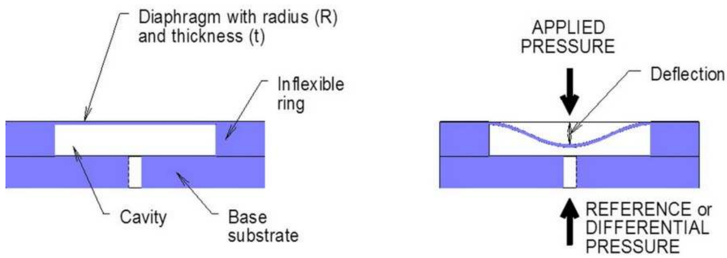

Fig. 1. A schematic of the 3D ceramic structure of a ceramic pressure sensor.

The sensor's characteristics depend on the construction, the dimensions and the material properties of the sensor body and the sensing elements (capacitor, PZT actuator and thick-film resistor). Some important characteristics of the LTCC material (DuPont 951) are summarized in Table 1.

Table 1. Some characteristics of the LTCC material (DuPont 951).

Property	Value
Young's modulus (GPa)	110
Density (g/cm^3)	3.1
Poisson's ratio (–)	0.17
Thermal expansion coefficient (×10^{-6}/K)	5.8
Thermal conductivity (W/mK)	3
Flexural Strength [MPa]	320

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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 are described by (1):

$$y(x) = \frac{3P\left(1-\nu^2\right)\left(R^2-x^2\right)^2}{16\,Y\,t^3}\,, \tag{1}$$

where the deflection y at the position x from the centre of the diaphragm is a function of the applied pressure, P, the material characteristics (Young's modulus, Y, and Poisson's ratio, ν) of the diaphragm, and the dimensions (thickness, t, and radius, R) of the diaphragm [6]. In practice, the pressure sensor behaviour is still considered as linear if the maximum deflection is smaller than one third of the diaphragm thickness.

The temperature has a noticeable influence on the material characteristics (Young's modulus, density and Poisson's ratio) and the fractional changes in the dimensions. The data on the temperature dependence of the Young's modulus of LTCC materials are not available. We therefore presumed that the values of the temperature coefficients (coefficients relating to the change of a property with temperature) of the Young's modulus (TCY) of the LTCC are between the TCY of alumina and the TCY of glass. Based on this, we used a value of -250×10^{-6}/K in our calculations. The 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 68×10^{-6}/K. Therefore, 100×10^{-6}/K was used as a rough estimation for the temperature coefficient of the Poisson's ratio (TCPR) of the glassy-alumina-filled LTCC material. The temperature-expansion coefficient (TEC) of LTCC materials is 5.8×10^{-6}/K. The temperature coefficient of the density (TCD) of LTCC materials for the temperature range between 25°C and 250°C can be calculated from the mass to volume ratio [12]. The calculated value of TCD for LTCC material with TEC of 5.8×10^{-6}/K is about -17.4×10^{-6}/K.

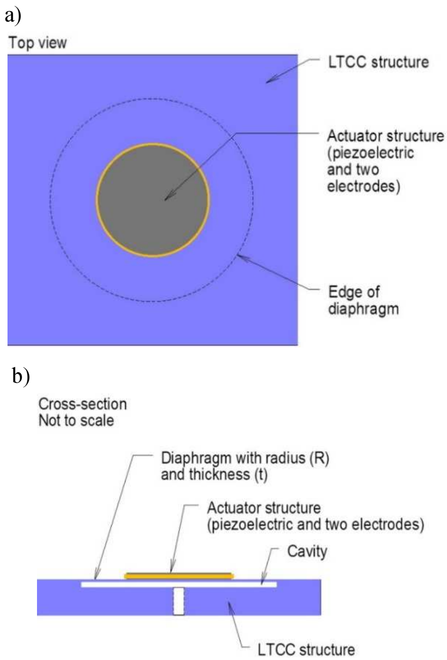

Fig. 2. A schematic of the three-dimensional ceramic structure of a ceramic resonance pressure sensor: a) the top-view and b) the cross-section.

The ceramic piezoelectric resonance pressure sensor behaviour depends on the piezoelectric properties of an actuator of a deformable diaphragm. The basic construction of the sensor is shown in Fig. 2.

The resonance sensor has an additional element – a piezoelectric actuator – for electro-mechanical stimulating oscillation of the diaphragm. The actuator is designed on the deformable diaphragm as a discrete device or as a vertical, thick-film structure, consisting of a bottom electrode, an active piezoelectric, and an upper electrode. By applying an electric field to the actuator, the actuator, through the piezoelectric effect, will generate stresses in the diaphragm, which will then induce vibration of the diaphragm that will be maximum at its natural resonance frequency. This resonance frequency for a circular, edge-clamped diaphragm is given by (2):

$$f_r = \frac{0.412 \cdot t}{R^2} \sqrt{\frac{Y}{\rho\left(1-\nu^2\right)}}\,, \tag{2}$$

where f_r is the resonance frequency of the diaphragm, which is a function of the material characteristics (Young's modulus, Y; density, ρ and Poisson's ratio, ν) of the diaphragm and its dimensions (thickness, t, and radius, R) [6].

The applied external static pressure will bend the diaphragm and will induce additional stresses. By changing the mechanical tensile state in the diaphragm, the resonance frequency will be shifted, which can be used as the output signal for the piezoelectric resonance pressure sensor. The static pressure can thus be monitored through changes in the resonance frequency.

3. Experimental work and results

The monolithic LTCC structure was made by lamination of 12 LTCC green tapes of DuPont 951PX at 70°C and at the pressure of 20 MPa. The laminated structure of green LTCC tapes was fired for 1 hour at 450°C (organic binder burnout) and 17 minutes at 875°C. The dimensions of the final LTCC structure are 60 × 40 × 2.5 mm^3. In the central part of this ceramic structure is a test ceramic resonance pressure sensor (Fig. 3). This sensor has a circular, edge-clamped diaphragm with the thickness of 200 µm. The diaphragm is located above the cavity with the diameter of 16 mm and the depth of about 1 mm. The cavity is connected by channel(s) with one or two pressure ports. Around the pressure sensor, in circular form, are an electric heater and a PTC (Positive Temperature Coefficient) temperature sensor, which was screen-printed together with other thick-film materials on the pre-fired LTCC structure. The functions of the heater and the temperature sensor are temperature regulation and control.

The test pressure sensor has a piezoelectric actuator, which is positioned in the middle of the diaphragm. Two types of sensors were prepared. In the first case (Fig. 3a), a discrete (bulk) actuator in the form of a disc with gold electrodes on both sides was glued on the diaphragm. The disc has the diameter of 6.0 mm and the thickness of 600 µm. In the second case (Fig. 3b), we made a thick-film piezoelectric actuator with the diameter of 6.2 mm and the thickness of 50 µm, which was screen-printed together with both electrodes on the diaphragm. After fabrication of the actuators, the bulk actuators were polarised with the electrical field of 100 kV/cm for 20 minutes at 160°C and then cooled to the room temperature. The thick-film actuators were polarised at the same electrical field, but in order to optimize at a lower temperature (80°C) and for a longer time (30 minutes).

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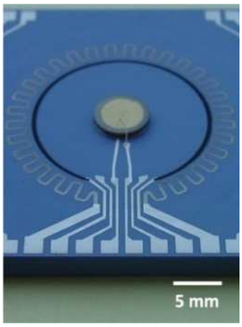
a)



b)

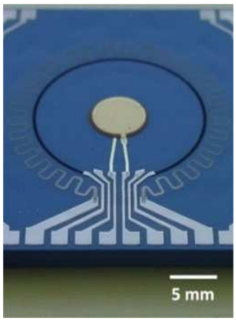


Fig. 3. A detailed schematic of the ceramic resonance pressure sensor: a) with a discrete (bulk) piezoelectric actuator in a disk form and b) with a screen-printed thick-film piezoelectric actuator.

Table 2 lists the electrical parameters, *i.e.*, the dielectric constant ε', the dielectric loss D, and the piezoelectric coefficient d_{33}, of the bulk piezoelectric actuator and thick-film piezoelectric actuator on the LTCC substrate.

Table 2. The electrical characteristics (dielectric constant ε′, dielectric loss D, and piezoelectric coefficient d_{33}) of a bulk piezoelectric actuator and a thick-film piezoelectric actuator on the LTCC substrate.

Characteristics	Bulk piezoelectric actuator	Thick-film piezoelectric actuator
Dielectric constant ε' (–)	1600	950
Dielectric loss D (–)	0.025	0.024
Piezoelectric coefficient d_{33} (pC/N)	700	80 [4]

The capacitance and the dielectric losses were measured with an HP-4284 Precision LCR Meter at 10 kHz. The dielectric constants were calculated from the capacitance and the geometry of the actuators. The values of the piezoelectric coefficient d_{33} were estimated by using the conventional Berlincourt method at 100 Hz with a "Piezometer system PM 10".

3.1. Characterisation of pressure sensors

Both types (with a bulk and with a thick-film piezoelectric actuator) of test ceramic piezoelectric resonance pressure sensors were fabricated and then tested in the pressure range from 0 to 70 kPa. In all cases the pressure was applied in the ceramic body (cavity). The capacitance, C, and the dielectric loss, D, of the piezoelectric resonance pressure sensors around the resonance frequency were measured with an HP4192A LF impedance analyser. At the resonance frequency, both parameters (C and D) significantly changed their values. The results for the capacitance and the dielectric loss of the resonance pressure sensor with a thick-film actuator without any applied pressure (0 kPa) are presented in Fig. 4 and the dielectric losses at different applied pressures (0−70 kPa) are presented in Fig. 5.

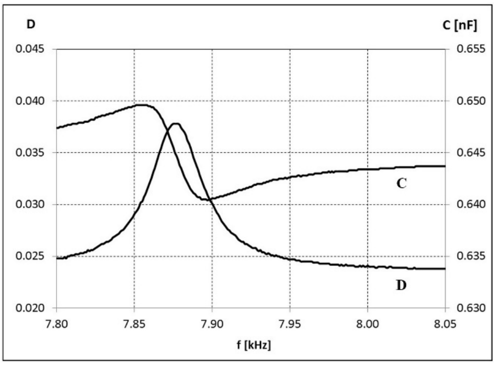


Fig. 4. The capacitance, C, and the dielectric loss, D, of the piezoelectric resonance pressure sensors.

The sensitivity of the pressure sensor, *i.e.*, the shifts of resonance frequency versus the applied pressure of the piezoelectric resonance pressure sensors with the thick-film actuator and with the bulk (disk) actuator, are presented in Fig. 6. The resonance frequencies of the pressure sensors with a thick-film actuator are around 8000 Hz and the average calculated pressure sensitivity is 9.2 Hz/kPa. In this case the measured resonance frequency is close to the calculated natural resonance frequency of the diaphragm, which is about 8800 Hz. In contrast, the resonance frequencies of the pressure sensors with a bulk actuator are around 5500 Hz and the average calculated pressure sensitivity is 3.1 Hz/kPa. Although the bulk actuator is "stronger" than the thick-film actuator (see the piezoelectric coefficients in Table 2), the resonance frequency of the pressure sensor is about 40% lower than the calculated value and the pressure sensitivity is about three times lower in comparison with the pressure sensors with a thick-film actuator. We presume that the relatively large mass of the bulk actuator reduces the resonance frequency and dampens the oscillation.

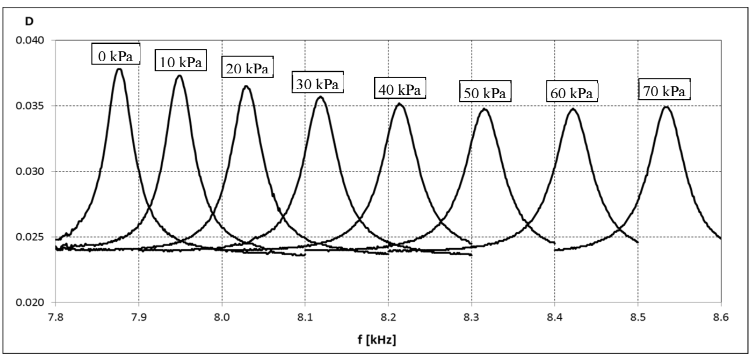


Fig. 5. The shift of the resonance frequency of the ceramic piezoelectric resonance pressure sensors at different applied pressures. The resonance frequencies were identified by measuring the dielectric loss, D, of the piezoelectric actuator.

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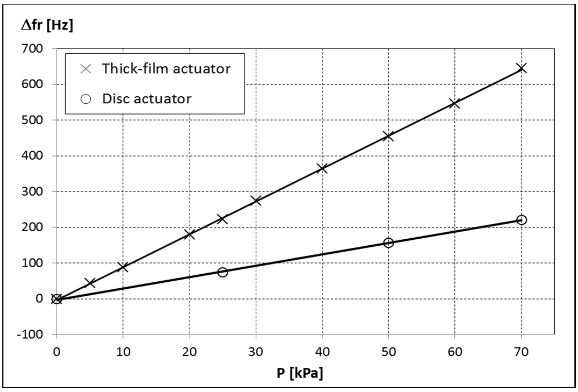

Fig. 6. The shift of resonance frequency versus the applied pressure of the piezoelectric resonance pressure sensors with the thick-film piezoelectric actuator and with the bulk (disc) piezoelectric actuator.

The results of typical characteristics of the ceramic piezoelectric resonance pressure sensors with a thick-film piezoelectric actuator and with a bulk (disc) piezoelectric actuator are summarized in Table 3.

Table 3. Some characteristics of the piezoelectric resonance pressure sensors with a bulk piezoelectric actuator and with a thick-film piezoelectric actuator.

Characteristics	Sensors with a bulk piezoelectric actuator	Sensors with a thick-film piezoelectric actuator
Resonance frequency at 0 kPa (Hz)	5500	8000
Linearity based on Pearson function (r-squared) (–)	0.9992	0.9991
Pressure sensitivity (Hz/kPa)	3.1	9.2

3.2. Temperature dependence of the ceramic pressure sensor

The calculated (2) resonance frequency of the LTCC, circular, edge-clamped diaphragm with the diameter of 16 mm and the thickness of 200 µm is about 8.8 kHz. The constant applied pressure of about 70 kPa deflects (1) this diaphragm in the centre by about 60 µm.

The main influence of the temperature on the deflection of the diaphragm (1) comes from the temperature dependence of the Young's modulus of LTCC materials, while the temperature dependence of the Poisson's ratio and the temperature dependence of the geometry (because of TEC) have minor effects. At the applied constant pressure of 70 kPa and at the temperature of 250°C the deflection increases by about 6%, because of the temperature dependence of the Young's modulus, and by about 0.13%, because of the temperature dependence of the geometry. At the same time, the deflection decreases by about 0.14%, because of the temperature dependence of the Poisson's ratio. Therefore, the overall deflection is about 6% higher at 250°C in comparison with the deflection at room temperature.

The impact of the temperature dependence of the material characteristics (Young's modulus, density and Poisson's ratio) and the fractional changes in the geometry on the resonance frequency of the resonance pressure sensor are graphically presented in Fig. 7.

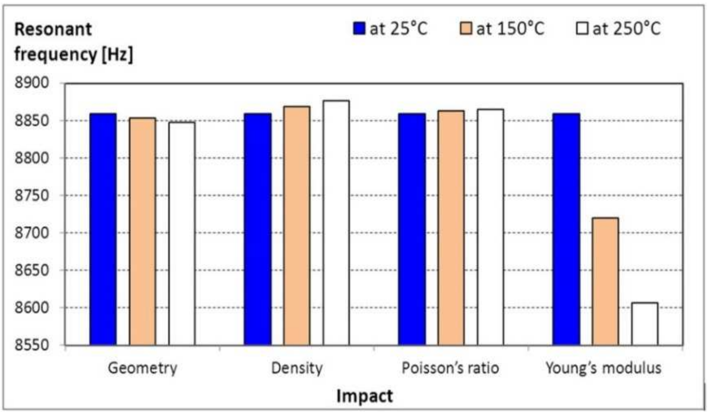

Fig. 7. The impact of the temperature dependence of the material characteristics (Young's modulus, density and Poisson's ratio) and the fractional changes in the geometry on the resonance frequency of the resonance pressure sensor with a thick-film piezoelectric actuator.

The main parameter of the ceramic structure (*i.e.*, the materials and the geometry) that affects the resonance frequency shift with temperature is the temperature dependence of the Young's modulus, while the temperature dependence of the Poisson's ratio, the temperature dependence of TEC and the temperature dependence of the density have minor effects on the temperature dependence of the resonance frequency (2). With an increase in the temperature up to 250°C the resonance frequency increases slightly (+0.07%) because of the temperature dependence of the Poisson's ratio, increases slightly (+0.20%) because of the temperature dependence of the density, and decreases slightly (–0.13%) because of the temperature dependence of the geometry. At the same time, the resonance frequency decreases by about 2.85% because of the temperature dependence of the Young's modulus. Overall, the resonance frequency decreases by about 2.7% with increasing the temperature from 25°C to 250°C.

The resonance frequencies from the measured data are shifted by around 8 kHz, depending on the pressure, whereas the pressure sensitivities are about 9.2 Hz/kPa.

The temperature dependence of resonance frequency is presented as a temperature coefficient of resonance frequency (*TKFr*), which is given by the (3):

$$TKF_r = \frac{\left(f_{T2} - f_{T1}\right)}{f_{T1}\,(T_2 - T_1)}, \tag{3}$$

where f_{T1} is the resonance frequency of the diaphragm at the temperature T_1 (25°C) and f_{T2} is the resonance frequency at the temperature T_2 (250°C). The calculated *TKFr* – because of the ceramic structure – is -120×10^{-6}/K.

4. Conclusions

Ceramic pressure sensors are mostly used in harsh environments. They have a good long-term stability and they contain no organic compounds. In comparison with semiconductor sensors they are more robust (less sensitive on environment conditions) and they can be used for higher pressure ranges (up to a few hundred bars). Piezo-resistive and capacitive types of ceramic pressure sensors are based on a mature technology and on commercially available, thick-film and ceramic materials. On the other hand, the piezoelectric resonance ceramic pressure sensor is a relatively new device. Its advantages are a relatively high pressure sensitivity, compatibility with the frequency as the output signal of the sensor, and – most importantly – a challenge for other sensors' applications based on the resonance principle.

We presume that a relatively high dependence of the resonance frequency on the temperature because of the ceramic structure (*i.e.*, the materials and the geometry) is stable and therefore it can be compensated by an electronic conditioning circuit. We can also expect an influence of the properties of the piezoelectric material on the behaviour of the sensor, which was, however, not evaluated in this initial study, but will be investigated in the next phase of the research work.

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References

[1] Partsch, U., Arndt, D., Georgi, H. (2007). A new concept for LTCC-based pressure sensors. *Proc. of 3rd International Conference and Exhibition on Ceramic Interconnect and Ceramic Microsystems Technologies CICMT 2007*, Denver, Colorado, USA, 367–372, CD-ROM.

[2] Belavič, D., Hrovat, M., Pavlin, M., Santo Zarnik, M. (2003). Thick-film technology for Sensor Applications. *Informacije MIDEM*, 33(1), 45–50.

[3] Maeder, T., Jacq, C., Briol, H., Ryser, P. (2003). High-strength Ceramic Substrates for Thick-film Sensor Applications. *Proc. of 14th European Microelectronics and Packaging Conference EMPC 2003*, Frieddrichshafen, Germany, 133–140, CD-ROM.

[4] Belavič, D., Hrovat, M., Holc, J., Santo Zarnik, M., Kosec, M., Pavlin, M. (2007). The application of thick-film technology in C-MEMS. *Journal Electroceramics*, 19, 363–368.

[5] Belavič, D., Santo Zarnik, M., Hrovat, M., Maček, S., Pavlin, M., Jerlah, M., Holc, J., Drnovšek, S., Cilenšek, J., Kosec, M. (2007). Benchmarking different types of thick-film pressure sensors. *Proc. of 3rd International Conference and Exhibition on Ceramic Interconnect and Ceramic Microsystems Technologies CICMT 2007*, Denver, Colorado, USA, 278–285, CD-ROM.

[6] Belavič, D. (2008). Piezoresistive, piezoelectric and capacitive pressure sensors. Tutorial: Ceramic pressure sensors – from materials to devices. *Proc. of 4th International Conference and Exhibition on Ceramic Interconnect and Ceramic Microsystems Technologies CICMT 2008*, Munich, Germany, CD-ROM.

[7] Santo Zarnik, M., Belavič, D., Maček, S., Holc, J. (2009) Feasibility study of a thick-film PZT resonant pressure sensor made on a prefired 3D LTCC structure. *International journal of applied ceramic technology*, 6(1), 9–17.

[8] Golonka, L.J., Malecha, K. (2012). LTCC Fluidic Microsystems. *Informacije MIDEM*, 42(4), 225–233.

[9] Kita, J., Moos, R. (2003). Development of LTCC-materials and Their Applications: an Overview. *Informacije MIDEM*, 38(4), 219–224.

[10] Belavič, D., Hrovat, M., Santo Zarnik, M., Makarovič, K, Benčan, A., Holc, J., Dolanc, G., Fajdiga, P., Hočevar, S., Pohar, A., Kovač, F., Hodnik, M., Konda, A., Jordan, B., Sedlakova, V., Sikula, J., Malič, B. (2014). An overview of LTCC based ceramic microsystems: from simple pressure sensors to complex chemical reactors. *Proc. of EDS' 14, Electronic Devices and Systems IMAPS CS International Conference 2014*, Brno, Czech Republic, XVI–XXI, CD-ROM.

[11] Santo Zarnik, M., Belavič, D., Sedlakova, V., Sikula, J., Majzner, J., Sedlak, P. (2012). Estimation of the long-term stability of piezoresistive LTCC pressure sensors by means of low-frequency noise measurements. *Sensors and actuators A Physical*, 199, 334–343.

[12] Lide, R.D. (2005). *Handbook of chemistry and Physics*. Boca Raton, CRC Press.