Capacitive Pressure Sensors Realized With LTCC Technology

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Abstrac.*: This work is focused on pressure sensors designed as a ceramic capsule consisting of a circular edge-clamped deformable diaphragm, which is bonded to the rigid ring, and the ring is fixed on the base substrate. These three elements form the cavity of the pressure sensor. The 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, and together with the geometry and flexibility of the diaphragm define the sensitivity of the sensor. The diaphragm with the diameter of 9 mm made with low-temperature cofired ceramic (LTCC) has a thickness of 200 µm and the distance between electrodes is about 70 µm. The initial capacitance is around 10 pF. The capacitive ceramic pressure sensor is the part of the electronic conditioning circuit with the frequency output. The typical output frequency is about 10 kHz and sensitivities are between 2.5 and 3.5 Hz/kPa.*

1. INTRODUCTION

In general, pressure sensors translate a physical quantity, i.e., pressure, into an electrical signal. The pressure sensor market has been dominated by the silicon pressure sensors [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 [4-8].

The most pressure sensors on the market are based on piezoresistive principle. This is mainly due to the fact that that the piezoresistive pressure sensors is relatively sensitive to applied pressure and its analogue output is linear in a wide pressure range while the output impedance is low. For capacitive pressure sensors the pressure sensitivity is intrinsically much higher than that of piezoresistive pressure sensors. The temperature effect on sensors' characteristics is inferior, 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.

This paper is focused on study a principle, investigating materials, and designing a capacitive pressure sensor using thick-film and LTCC materials and technology.

2. SENSOR STRUCTURE

Most thick-film or ceramic pressure sensors are made with deformable diaphragms [4]. The deformation is induced by the applied pressure and then converted by changing the characteristics of the thick-film electronic components or the structures 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 the base substrate. These elements form the cavity of the pressure sensor. The cross-section of this type of thick-film pressure sensor is schematically shown in Figures 1 and 2.

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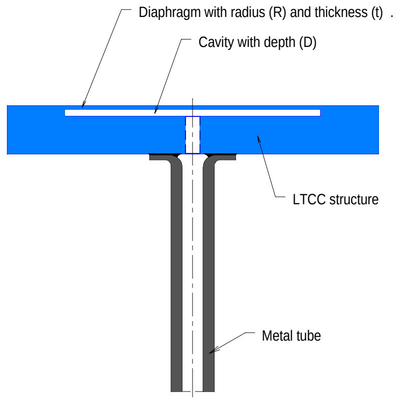

Figure 1. The cross-section of the LTCC structure of a thick-film pressure sensor (schematic and not to scale)

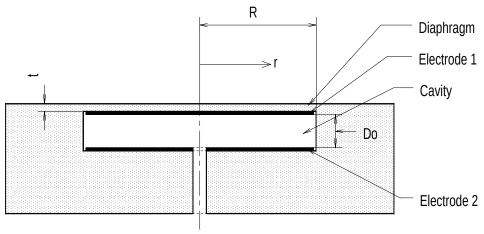

Figure 2.a. The cross-section of a capacitive pressure sensor without applied pressure (schematic, not to scale)

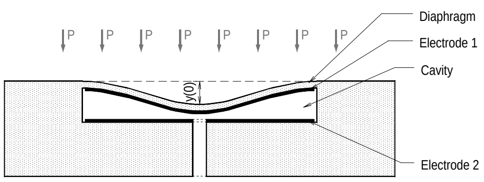

Figure 2.b. The cross-section of a capacitive pressure sensor with applied pressure (schematic and not to scale)

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)

$$y(r) = \frac{3P\left(1-\nu^2\right)\left(R^2-r^2\right)^2}{16\,E\,t^3} \qquad (1)$$

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, ν) of the diaphragm, and the dimensions (thickness, *t*, and radius, *R*) of the diaphragm (Figures 1 and 2).

The sensors' characteristics depend on the construction, the dimensions and the material properties of the sensor body and sensing elements [4,7,8]. Some of the mechanical characteristics of a LTCC (Du Pont 951) are summarized in Table 1. LTCC materials have a great deal of flexibility when designing the 3D construction [3-6]. The LTCC construction also has the advantage of a relatively low modulus of elasticity when compared with alumina. The disadvantage, however, is the low flexural strength and the possible problems with fatigue [3-8].

Table 1. Some material characteristics of one of the LTCC materials

Property	**DP951**
Young's modulus E (GPa)	110
Density (g/cm^3)	3.1
Thermal expansion coefficient ($\times 10^{-6}/K$)	5.8
Thermal conductivity (W/mK)	3
Flexural Strength (MPa)	320

3. Pressure sensor theory

The capacitive pressure sensor principle operation is based on the fractional change in capacitance ($\Delta C/C$) induced by the applied pressure. The capacitance change is due to the changing distance between the electrodes of the capacitor [9-13]. These electrodes are within the cavity of the LTCC structure (Figures 1 and 2). The bottom electrode (Electrode 2) of the capacitor is on the rigid substrate and the upper electrode (Electrode 1) is on the deformable diaphragm. The areas of the electrodes and the distance between them define the value of the initial capacitance (C_0) of the pressure sensor. The distance between the electrodes (D) is subtracted from cavity depth (d) and the thickness of both electrodes. When the applied pressure is within the range and the deflection of the diaphragm y(r) 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)

$$C(P) = \varepsilon_0 \cdot \varepsilon_r \cdot \int_0^R \frac{2\cdot\pi\cdot r\cdot dr}{D_0 - y(r)} \qquad (2)$$

where C is the capacitance under an applied pressure P, ε_0 is the permittivity in vacuum, ε_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.

4. EXPERIMENTAL

The construction of the thick-film or ceramic capacitive sensor is very similar to other thick-film pressure sensors. 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 air capacitor of the test samples of the thick-film capacitive pressure sensor was designed as a cavity with a diameter of 9.0 mm and a height of about 80 µm. 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 µm. The fabricated samples, which are shown in Figure 3, were tested in the low-pressure range, where the sensor's response is linear. The range of the pressure test was from 0 to 70 kPa.

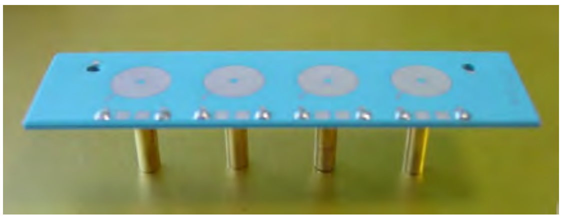

Figure 3. Four thick-film capacitive pressure sensors integrated in a LTCC structure

The initial capacitances of the pressure sensors are between 8 and 10 pF. The capacitive ceramic pressure sensor is 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 relative output frequency versus applied pressure is shown in Figure 4. The calculated pressure sensitivities from the measured data are between 2.5 and 3.5 Hz/kPa.

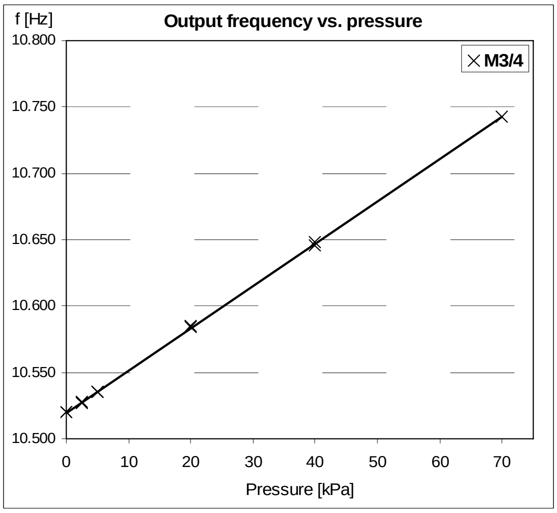

Figure 4. The output frequency versus the applied pressure of the capacitive pressure sensor with the electronic conditioning circuit

The fabricated samples, which are shown in Figure 3, were tested also at different temperatures. The range of the pressure test was from 0 to 70 kPa at five different temperatures (-25°C, 0°C, 25°C, 50°C and 75°C). The relative change in the initial capacitance of the pressure sensor versus the different temperatures is shown in Figure 5 and the relative output frequency versus applied pressure at different temperatures is shown in Figure 6. The calculated temperature dependence of the output frequency is between -60 and -120 Hz/K.

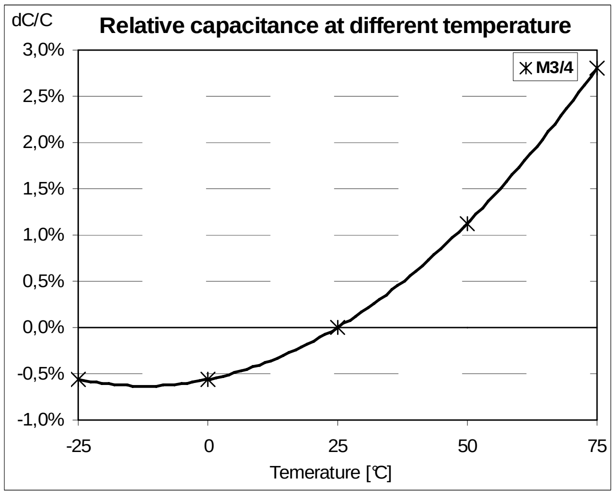

Figure 5. The relative change of initial capacitance at different temperatures for the capacitive pressure sensor

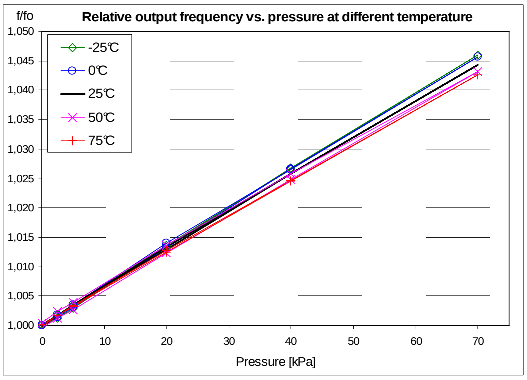

Figure 6. The relative output frequency at different temperatures versus the applied pressure of the capacitive pressure sensor with the electronic conditioning circuit

5. Conclusion

The fabrication of capacitive pressure sensors using thick-film and LTCC materials and technology is challenging opportunity for pressure sensors market. The applied pressure generates 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 their repeatability. In general a capacitive pressure sensor has advantages of high sensitivity, low temperature dependence, suitability for high-temperature applications, usable in different gases or liquid media, a robust structure, low energy consumption, compatibility with the frequency as the output signal of the sensor, and a low sensitivity to environmental effects. However, 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. A reduction of the parasitic capacitance effect can only be achieved by suitable interface electronics.

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