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Evaluation of piezoresistive ceramic pressure sensors using noise measurements

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Abstract: The development of low-temperature co-fired ceramic (LTCC) technology is increasing the interest in ceramic pressure sensors (CPS). This technology and materials in combination with conventional thick-film technology offers a feasible solution to increase the sensitivity of pressure sensors and the flexibility in design, both with the aim to replace silicon-based pressure sensors in some applications. The sensor characteristics, i.e., offset stability and sensitivity, are always influenced by the level of electronic noise. We are concentrating our efforts on the use of low-frequency noise as a diagnostic tool for a reliability improvement and sensitivity increase. 1/f noise is dominant in the low-frequency region. It is given by two components; one is connected to the material structure and the second one is influenced by the defects and imperfection in the structure. The measurements of the electronic noise level could be used for an evaluation of different technologies in order to tune the pressure sensor technology and for the evaluation of sensor quality within one technology. We show the correlation between the noise of the sensing resistor technology and the noise of the output voltage on the measured pressure sensor.

Key words: LTCC, noise spectral density, sensitivity, resolution

Evaluacija piezouporovnih keramičnih senzorjev tlaka z meritvijo 1/f šuma

Povzetek: Z razvojem keramičnih tehnologij in materialov z nizko temperaturo žganja (LTCC) se povečuje tudi interes za keramične senzorje tlaka (KST), ki so primerna alternativa silicijevim senzorjem tlaka za nekatera specialna področja uporabe. LTCC tehnologija ponuja nekaj prednosti v primerjavi s konvencionalnimi keramičnimi tehnologijami in je zelo primerna za izdelavo tridimenzionalnih senzorskih struktur. Ena pomembnih prednosti je relativno nizek modul elastičnosti LTCC keramike, ki omogoča doseganje večjih deformacij pod tlačno obremenitvijo in s tem relativno večjo občutljivost senzorja glede na dimenzije. Karakteristike senzorja (stabilnost ničelnega izhoda in občutljivost) pa so odvisne tudi od velikosti električnega šuma izhodnega signala. V tem prispevku obravnavamo meritev nizkofrekvenčnega šuma kot diagnostično orodje za ovrednotenje senzorskih karakteristik in analizo možnosti za izboljšanje resolucije senzorja. 1/f šum je dominanten v nizkem frekvenčnem področju. Podan je z dvema komponentama; prva komponenta je povezana s strukturo uporabljenih materialov in druga komponenta predstavlja vpliv defektov in neidealnosti strukture. Tako lahko meritve električnega šuma uporabimo za evaluacijo različnih materialov in postopkov in na ta način usmerjeno izboljšamo tehnologijo izdelave senzorjev za doseganje optimalnih rezultatov. Predstavili smo korelacijo med šumom debeloplastnih senzorskih uporov in šumom izhodnega signala, ki pomembno vpliva na resolucijo senzorja.

Ključne besede: LTCC, elektronski šum, občutljivost, resolucija

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1. Introduction

The pressure sensor market is dominated by silicon pressure sensors. However, ceramic pressure sensors with a flexible diaphragm have been available for more than 25 years. Ceramic pressure sensors (CPSs), in comparison with semiconductor sensors, are larger, more robust and have a lower sensitivity. But, some new technologies developed in the past few years increase the sensitivity and offer a flexible architecture, with the aim to replace the silicon-based pressure sensors in some applications. One of these technologies is low-temperature co-fired ceramic (LTCC) technology. Ceramic pressure sensors fabricated using low-temperature co-fired ceramic substrates were studied. LTCC technology and materials in combination with conventional thick-film technology offers a feasible solution to increase the sensitivity of pressure sensors [1, 2, 3]. For the sensor sensitivity increase it is necessary to suppress the electronic noise of the sensor itself, in order to increase the signal-to-noise ratio. The electronic noise level depends on the used materials, i.e., substrates, resistive and conductive pastes, and the resistor geometry. Low-frequency noise in pressure sensors appears during the charge carriers' transport as a result of the carrier interaction with interfaces and defects, on the boundaries among the conductive grains in the resistors structure and on the other scattering centres. The possibility of using noise measurements in the analysis, diagnostics and prediction of the reliability of thick-film resistors was studied before [4, 5].

2. Experimental

2.1 Measured samples

The pressure sensors were fabricated on pre-fired LTCC structures with cavities and thin deformable diaphragms made of the LTCC tape Du Pont 951. On the top of the round diaphragm, four thick-film cermet resistors were connected in a Wheatstone bridge. A photograph of the measured pressure sensor is shown in Fig. 1.

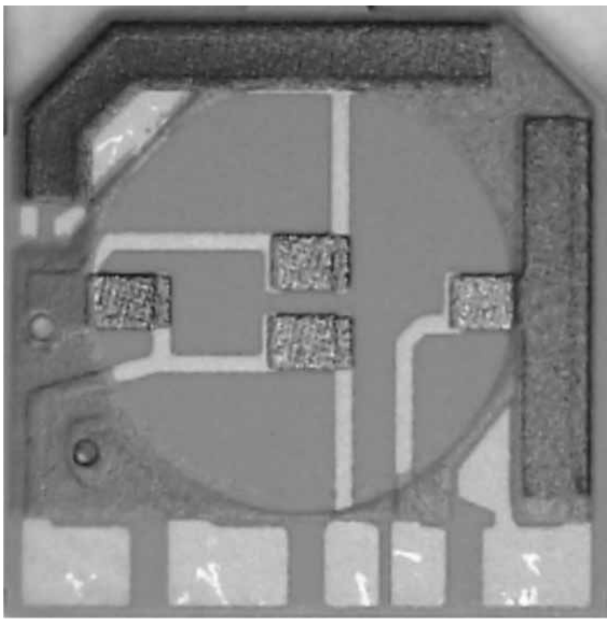

Figure 1: Photograph of the measured pressure sensor (lateral dimensions of 10 mm x 10 mm).

The equivalent electrical circuit of the measured pressure sensor is shown in Fig. 2. Resistors R1, R2, R3 and R4 are sensing resistors on the diaphragm, while resistors R5 and R6 are designed for the tuning of the bridge output and placed at the edges of the substrate (see Fig. 1).

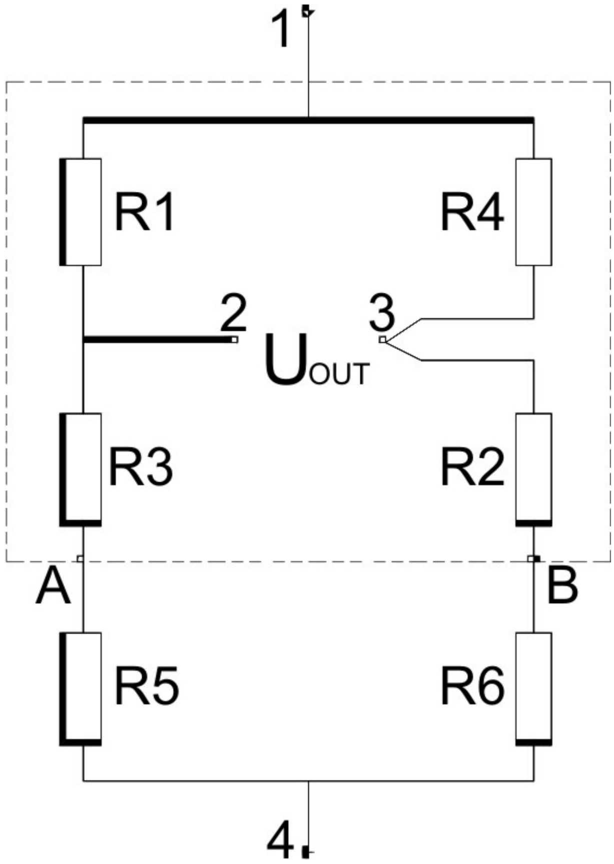

Figure 2: An equivalent electrical circuit of the pressure sensor.

Two types of resistor materials were used: Du Pont resistive paste 2041 (sheet resistance is about 10 kOhm; Gauge Factor is about 10 [6]) – further denoted as Type 1, and Electro Science Laboratories resistive paste 3414 (sheet resistance is about 36 kOhm; Gauge Factor is about 19 [6]) – further denoted as Type 2. Conducting paste DuPont 6143 (Ag/Pd paste) was used for contacts.

The pressure sensor sensitivity is influenced by the materials used for the active resistors R1 to R4. To evaluate the influence of different manufacturing technologies on the sensor noise, special test samples consisting of 12 thick-film resistors with different geometries were prepared on a common LTCC substrate. The layout of these resistors is shown in Fig. 3.

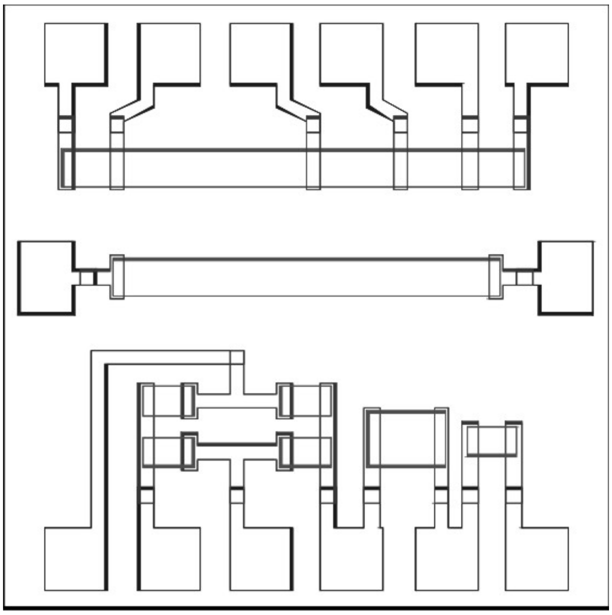

Figure 3: The layout of the test thick-film resistors on the common LTCC substrate (16.6 mm x 16.6 mm).

The test resistors were prepared by different technologies using two different resistive pastes and two conducting pastes (Pd/Ag, 7484 and Au, 8837). The resistors were either screen printed on the green tape and co-fired with the substrate, or printed on the pre-fired LTCC substrate. The resistors made with six different technologies, summarized in Table 1, were evaluated.

Table 1: Description of the technologies for the measured samples

Technology	Resistive paste	Conducting paste	LTCC substrate
TECH 1	2041	7484	green
TECH 2	3414	7484	green
TECH 3	2041	7484	pre-fired
TECH 4	3414	7484	pre-fired
TECH 5	2041	8837	pre-fired
TECH 6	3414	8837	pre-fired

2.2 Low-frequency noise measurements

Low-frequency noise was measured using the measuring set-up according to Fig. 4. The measured noise voltage is pre-amplified using an ultra-low-noise preamplifier a background noise spectral density of 10^{-18} V^2/Hz. Then the signal passes through the band-pass filter and is amplified to the required level. The signal is digitalized and the noise spectrum is calculated in the real time using Fast Fourier transforms.

We measured the fluctuation of the output voltage U_{OUT} on the pressure sensor (voltage between the terminals 2 and 3 – see Fig. 2) for different values of voltage applied on the sensor (between terminals 1 and 2). The output voltage noise spectral density measured for sensor of Type 34 is shown in Fig. 5. The voltage noise spectral density is 1/f type in the range 1–1000 Hz and it can be described by the formula:

$$S_U = \frac{\alpha_H \cdot U_x^2}{N \cdot f} \tag{1}$$

where S_U is the voltage noise spectral density, U_x is the DC voltage applied to the measured sample, N is the total number of fluctuators, f is the frequency and α_H is the Hooge parameter.

For a stationary and ergodic stochastic process the noise spectral density is proportional to the square of the voltage (see Fig. 6). It is very convenient to normalize the measured noise spectral density for the applied voltage and frequency and to use a noise quality indicator C_Q for the sensor/resistor quality evaluation.

C_Q is a dimensionless parameter with a value dependent on the sample quality and reliability.

$$C_Q = S_U \cdot \frac{f}{U_x^2} = \frac{\alpha_H}{N} \tag{2}$$

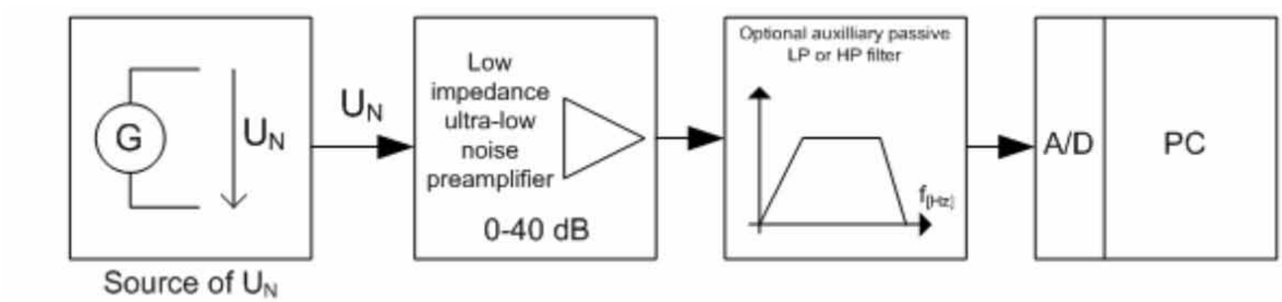

Figure 4: Block diagram of the noise experimental set-up.

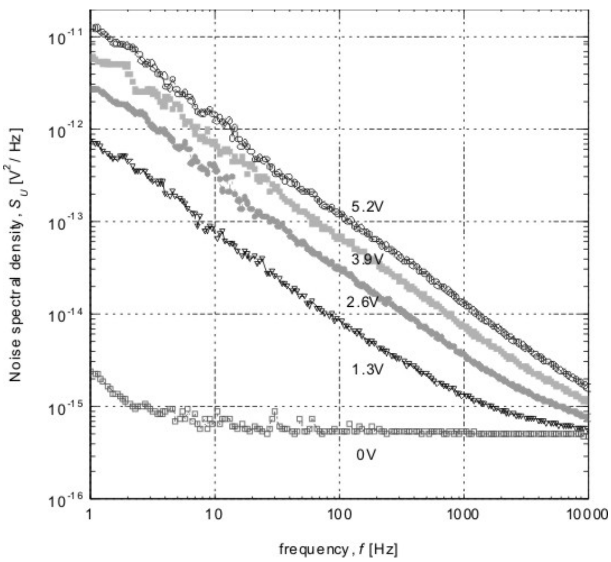

Figure 5: Output voltage noise spectral density vs. frequency for different applied voltages - measured for the pressure sensor Type 2.

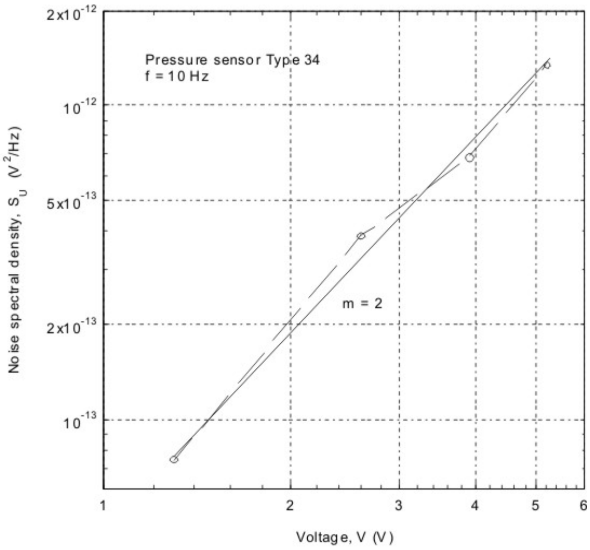

Figure 6: Output voltage noise spectral density vs. applied voltage for the pressure sensor Type 2.

For the comparison of different technologies we measured the low-frequency noise of resistors of sizes 1.5 mm x 1.5 mm, 0.8 mm x 0.8 mm, and the noise of the output voltage on the bridge given by four resistors of size 0.8 mm x 0.8 mm. Two samples of technology 5 and three samples of the other technologies were evaluated. The noise quality indicator C_Q calculated for resistors of size 0.8 mm x 0.8 mm and 1.5 mm x 1.5 mm for different technologies is shown in Figs. 7 and 8, respectively.

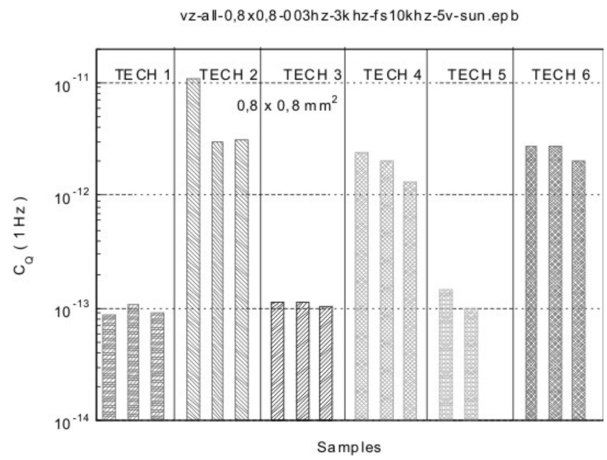

Figure 7: Noise quality indicator C_Q calculated for resistors 0.8 x 0.8 mm^2 for different technologies.

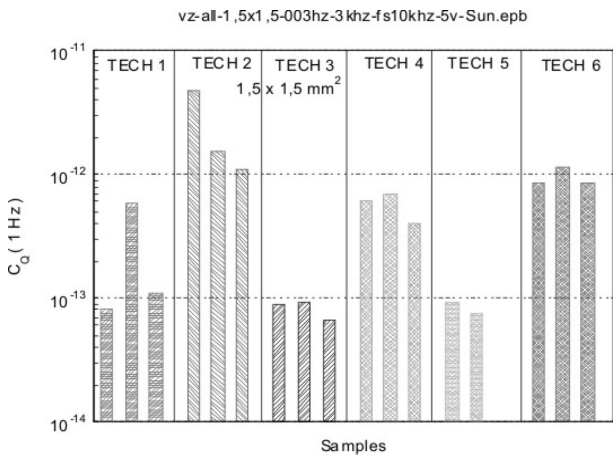

Figure 8: Noise quality indicator C_Q calculated for resistors 1.5 x 1.5 mm^2 for different technologies.

We can see that the noise quality indicator C_Q strongly depends on the resistive paste type. The value of C_Q calculated for the technologies TECH 2, TECH 4 and TECH 6 is about one order of magnitude higher than that obtained for TECH 1, TECH 3 and TECH 5, respectively. Some further influence of the LTCC substrate preparation is observed in the measured data as follows. For the resistors printed on the green tape and co-fired with the substrate a larger distribution of measured data is observed (TECH 1 and TECH 2) compared to the results obtained for the resistors prepared by the same combination of thick-film conductors and resistors that were screen printed on the pre-fired LTCC substrate (TECH 3 and TECH 4). The influence of the resistor size is visible over all technologies. For smaller resistors the noise level increases.

The output voltage noise spectral density frequency dependence measured for an applied voltage of 5.08 V for three bridges of technology TECH 3 and TECH 4, respectively, is shown in Fig. 9. We can see that the output voltage noise spectral density is two orders of magnitude higher for TECH 4 than for TECH 3.

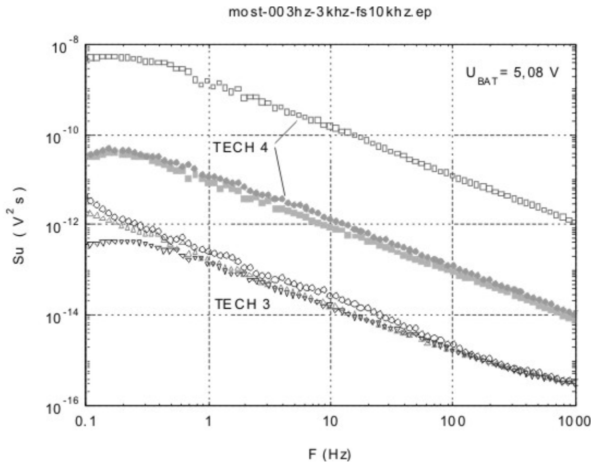

Figure 9: Output voltage noise spectral density vs. frequency for applied voltage 5.08 V - measured for three bridges of technology TECH 3 and TECH 4, respectively.

When we compare the results for the voltage noise spectral density obtained for the single resistor and for these resistors connected to the bridge, we can see that the difference between the technologies TECH 3 and TECH 4 increased for an order of magnitude in the case of resistors connected in the bridge. The value of the output voltage fluctuation influences the offset and the sensitivity of the final pressure sensor.

3. Conclusion

Ceramic pressure sensors based on LTCC technology were evaluated using low-frequency noise measurements. The sensor output voltage noise spectral density is 1/f type in the range 1 to 1000 Hz.

The pressure sensor output voltage noise level influences the background value of the sensitivity of the sensor and this depends on the used material and the technology of the sensing resistors. For the evaluation of the influence of resistive materials (Du Pont 2041 and ESL 3414) and manufacturing technology (co-fired and post-fired resistors) on the sensor noise samples of thick-film resistors prepared on LTCC substrate were studied. A strong influence of the resistive paste type was observed – the difference between the pastes in our case is about one order of magnitude. Some influence of the other parameters, such as LTCC substrate preparation and resistor size, are also presented. The resistors screen printed on the green tape and co-fired with the substrate show a larger distribution of measured data compared to the samples prepared on the pre-fired LTCC substrate. The voltage noise level increases with the decreasing size of the resistors. The influence of the resistive paste type is even more pronounced in the case of the connection of the resistors in the bridge. The difference between the technology TECH 3 and TECH 4 is an order of magnitude for the single resistors and increased up to two orders of magnitude for the case of resistors connected in the bridge. The use of the different conductors in this case study did not reveal a significant influence on the measured results. The best results were obtained with TECH 3 and 5, i.e., the 2041 resistors on the prefired LTCC substrates.

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