Comparison of the Intrinsic Characteristics of LTCC and Silicon Pressure Sensors by Means of 1/f Noise Measurements

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Abstract. *A pressure sensor with high resolution is of key importance for precise measurements in the low-pressure range. The intrinsic resolution of piezoresistive ceramic pressure sensors (CPSs) mainly depends on their functional sensitivity and the electronic noise in the thick-film resistors. Both the sensitivity and the noise level depend on the material and the structural properties, and the dimensions of the sensing structure. In general, the sensitivity can be increased and the noise can be reduced by using additional electronics for the signal processing, but this makes the sensor bigger, more complex and more expensive. In this study we discuss the technological limits for downscaling the sensor's pressure range without any processing of the sensor's signal. The intrinsic resolution of the piezoresistive pressure sensors designed for the pressure range 0 to ±100 mbar and realized in LTCC (Low Temperature Cofired Ceramic) technology was evaluated and compared to the resolution of a commercial 100-mbar silicon pressure sensor. Considering their different typical sensitivities, the resolutions of about 0.02 mbar and 0.08 mbar were obtained for the CPS and the silicon sensors, respectively. The low-frequency noise measurements showed that the noise characteristics of both sensors were not influenced by the pressure loads.*

Keywords

LTCC pressure sensor, intrinsic resolution, noise spectral density

1. Introduction

Ceramic pressure sensors (CPSs) made using LTCC (Low Temperature Cofired Ceramic) technology have proven to be appropriate for applications in the low-pressure ranges [1-3]. A key requirement for measurements in the low-pressure range is a fine resolution of the whole sensor system. The intrinsic resolution of any pressure sensor is defined by the smallest changes in the pressure that can be detected and accurately measured, and depends on the sensitivity and stability of the sensing elements, both of which are influenced by a certain level of electronic noise. In this sense the finest resolution can be achieved for the highest sensitivity and the lowest noise level. The sensitivity of a piezoresitive CPS is limited by the sensor's maximum dimensions and the material properties of the ceramic structure as well as the functional thick-film resistors, i.e., the Young's modulus of the LTCC material and the piezoresistive properties of the thick-film resistors. The noise in thick-film resistors depends on the resistor material, the contacts and the geometry/dimensions [4], [5]. The exploitation of the low-frequency noise for the quality and reliability evaluation of the electronic components, namely the sensors, was studied by many authors [6-11]. After optimizing the sensor geometry and selecting the most appropriate resistor and conductor materials, the noise of the sensor system can be further reduced only by adding additional electronics for the signal processing, such as filtering, usually achieved at the expense of the dynamic behavior of the sensor. This results in a further increase of the sensor's complexity and the final cost. An example of the design optimization of silicon piezoresistive pressure sensors considering the output signal-to-noise ratio is discussed in [14].

In this work we present the results of an investigation of the technological limits for downscaling a sensor's pressure range without any further processing of the sensor's signal. The piezoresistive LTCC pressure sensors [5] designed for the pressure range 0 to ± 100 mbar were manufactured and characterized. The measurements of the noise spectral density of the sensor's output-voltage fluctuation and calculations of the background sensitivity are discussed. The CPS's intrinsic resolution was compared to the resolution of a commercial, 100-mbar, silicon pressure-sensor die AC3030-100 (Acuity Incorporated). The influence of the pressure load on the low-frequency noise level was studied for both the LTCC-based and silicon pressure sensors.

2. Experimental

2.1 Sensor Prototypes

The piezoresistive CPSs considered in this case study were made using DuPont 951 tapes and 2041 thick-film resistor material. Four thick-film resistors were realized onto a deformable diaphragm. Each of these resistors acts as a strain gauge [7]. These four sensing resistors are electrically connected in a Wheatstone-bridge configuration and excited with a stabilized bridge voltage (Vs). The prototypes were designed for the relatively low-pressure range of 0- 100 mbar. A representative sample and the electrical circuit with the functional thick-film piezoresistors R_1-R_4 in the bridge connection and the resistors R_5 and R_6 aimed at balancing the bridge are presented in Fig. 1.

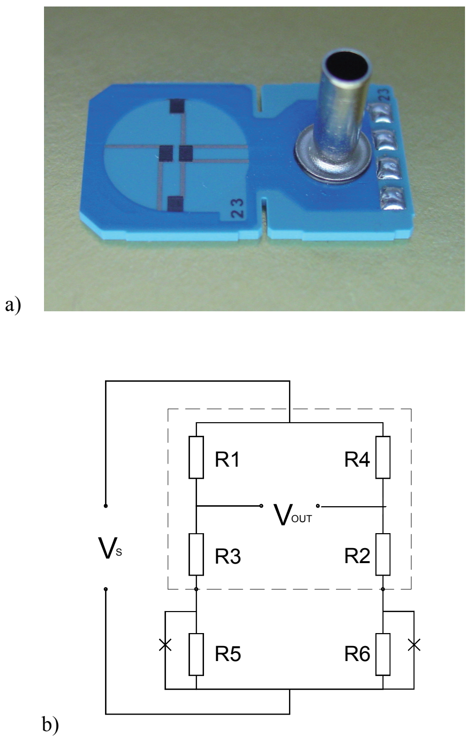

Fig. 1. a) A prototype of the LTCC-based CPS used for the evaluation of the intrinsic sensitivity, b) the Wheatstone-bridge connection of the sensing resistors R_1-R_4 and the resistors R_5 and R_6 aimed at balancing the bridge.

The CPS's characteristics were compared with the characteristics of the silicon pressure-sensor die AC3030-100 glued and wire bonded on the Al_2O_3 substrate. The test silicon pressure sensors with AC3030 dies were prepared in the HYB Company using their standard technological procedure (Fig. 2.).

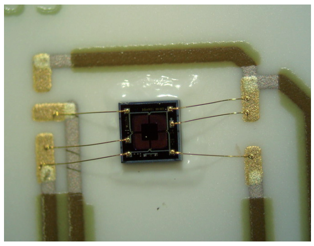

Fig. 2. The silicon pressure-sensor die glued and bonded on the Al_2O_3 substrate.

2.2 Characterization

The sensors were normally characterized in the pressure range 0- 100 mbar at a DC supply voltage (Vs) of 5 V. All the measurements were performed under controlled conditions in a temperature/humidity chamber. The normal conditions were 25°C and 50% RH. The accuracy of the Pace 6000 pressure controller used for the evaluation of the sensor's sensitivity is 0.035 mbar. The typical sensitivity of the CPSs was 14 µV/V/mbar, while the sensitivity of the AC3030-100 sensor dies was typically 65 µV/V/mbar. The measured characteristics of the CPSs and the silicon pressure sensors are presented in the same graph in Fig. 3.

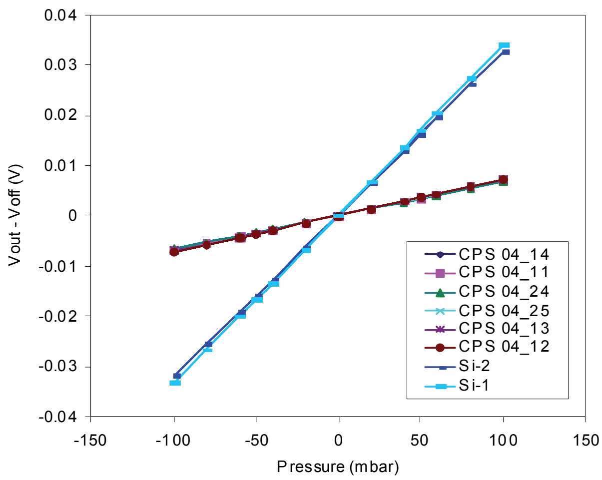

Fig. 3. The characteristics of the LTCC pressure sensors (denoted CPS 04_xx) and the silicon pressure-sensor dies glued and bonded on the Al_2O_3 substrate (Si-1 and Si-2).

Further experimental analyses of the stability, repeatability and hysteresis of the CPS prototypes revealed the limitations of the achievable resolution of the sensor, as described in the following. The continuous measurements of the offset stability within the initial 24 hours after switching on the supply voltage revealed noticeably higher fluctuations of the offset voltage of the silicon sensors than the offset voltage of the CPSs. The continuous measurements of the offset voltage are presented in Fig. 4.

It is evident that the fluctuations of the offset voltage of the silicon pressure sensors are significantly higher. However, due to the few-times-higher sensitivity such a presentation of the results can distract us from the actual situation. For this reason further tests were performed to clarify the situation.

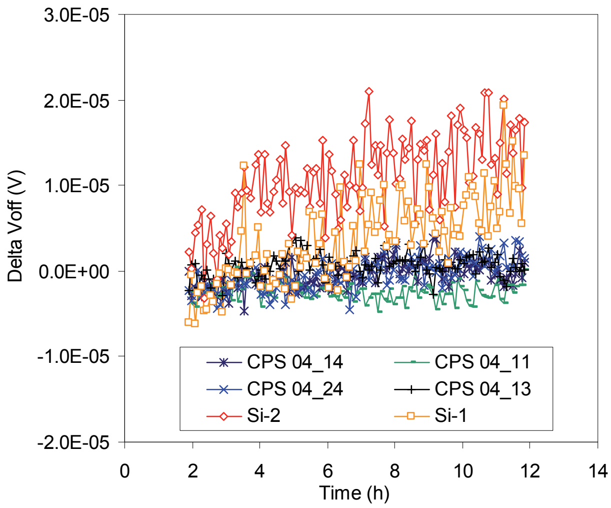

Fig. 4. The continuous measurements of the offset voltage of the LTCC pressure sensors denoted CPS04_xx and the silicon pressure-sensor dies glued and bonded on the Al_2O_3 substrate (Si-1 and Si-2).

In order to reduce the influence of the measurement set-up, which was designed for measurements of several sensors at the same time and to improve the accuracy of the measurements under the pressure loads set by the controller, the measurements were also performed in a narrow segment of the actual pressure range. The results are presented in Fig. 5, which shows the calibrated output of the selected CPSs and silicon pressure sensors, and the deviation of the sensors' output from the applied pressure in the range from -5 to +5 mbar with a step of 0.5 mbar. These results show that there is no significant difference between the error of the sensor's output signal between the CPSs and the silicon sensors. For both sensors a deviation of less than 0.1 mbar was obtained. Since the dynamic nature of

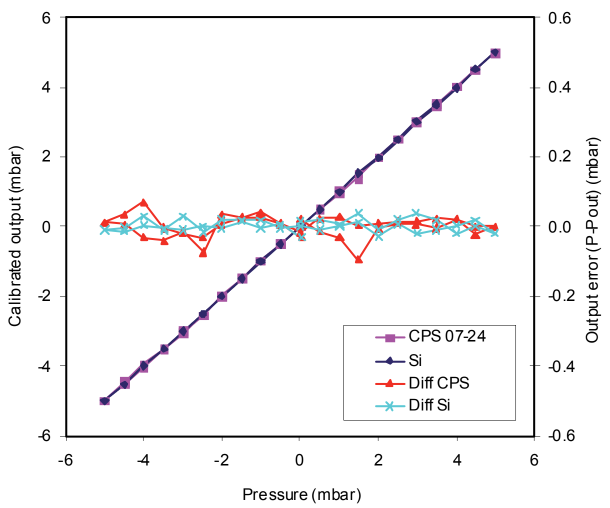

Fig. 5. Calibrated output of the sensors (Y axis on the left) and the output error, i.e., the deviation of the measured pressure from the applied pressure (Y axis on the right) evaluated in the pressure range from -5 to +5 mbar.

the measurements under controlled pressure loads can influence the accuracy of the measurement system, further measurements of the unloaded sensors, i.e., the offset voltages, were performed, and the noise measurements and analysis were carried out to confirm these results. Based on these measurements the intrinsic resolution was assessed as described in the following.

2.3 Low-Frequency Noise vs. Resolution

The fluctuation of the sensor's output voltage was measured for the applied voltage of 5.5 V using a standard measurement set-up [3]. The noise spectral density S_U of the measured signal was calculated in the frequency range 1 to 1000 Hz (see Figs. 6 and 7). In this frequency range the noise spectral density is given by two components, i.e., the thermal noise and the 1/f noise spectral density.

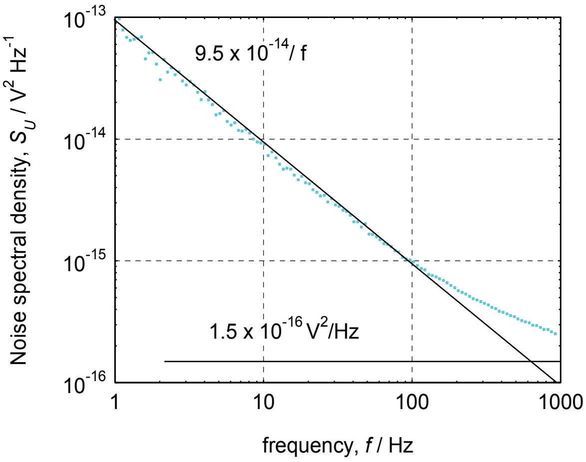

Fig. 6. Output-voltage noise spectral density S_U vs. frequency measured for the LTCC pressure sensor CPS 04-24 on a log-log scale. S_U is given by two components: thermal noise spectral density $S_{UTh} = 1.5 \cdot 10^{-16}$ [V^2/Hz] and 1/f noise spectral density $S_{U\,1/f} = 9.5 \cdot 10^{-14}$/f [$V^2$/Hz].

The noise-voltage value u_N can be calculated from the noise spectral density as:

$$u_N = \sqrt{S_U \cdot \Delta f} = \sqrt{\int_{f_i}^{f_f} S_U(f)df} \tag{1}$$

where $\Delta f = f_f - f_i$ is the frequency range being considered. If we want to determine the background resolution of the pressure sensor, it is necessary to calculate the noise voltage value in the frequency range given by the input RC filter of the DC voltmeter used for the sensor's output-voltage measurement. Considering the frequency range 1 to 1000 Hz we calculated the noise voltage value for the silicon and LTCC-based sensors. The output-voltage noise spectral density S_U frequency dependence measured for the LTCC pressure sensor, CPS 04-24, is shown in Fig. 6. We have fitted this dependence with the equation $S_U(f) = 9.5 \cdot 10^{-14}/f + 1.5 \cdot 10^{-16}$ [V^2/Hz], where the first component represents the 1/f noise and the second component the thermal noise. According to (1) we obtain:

$$u_{N,LTCC} = \sqrt{\int_{1}^{1000} (9.5 \cdot 10^{-14} / f + 1.5 \cdot 10^{-16}) df} = 9 \cdot 10^{-7} V \cdot$$

The output-voltage noise spectral density S_U frequency dependence measured for the silicon pressure sensor is shown in Fig. 7. We fitted this dependence with the equation S_U $(f) = 1.56 \cdot 10^{-10}/f^{1.15} + 1.0 \cdot 10^{-14}$ [V^2/Hz], where the first component represents the 1/f noise and the second component the thermal noise. According to (1) we obtain:

$$u_{N,Si} = \sqrt{\int_{1}^{1000} (1.56 \cdot 10^{-10} / f^{1.15} + 1.0 \cdot 10^{-14}) df} = 2.61 \cdot 10^{-5} V \cdot$$

We can see that the noise voltage for the LTCC sensor is less than 1 µV, while the value calculated for the silicon sensor is above 26 µV. Considering typical sensitivities of the LTCC sensors of 14 µV/V/mbar and 65 µV/V/mbar for the silicon sensor we can obtain (for the applied voltage of 5.5 V) a resolution of about 0.02 mbar for the LTCC sensor (CPS04-24) and about 0.08 mbar for the silicon sensor.

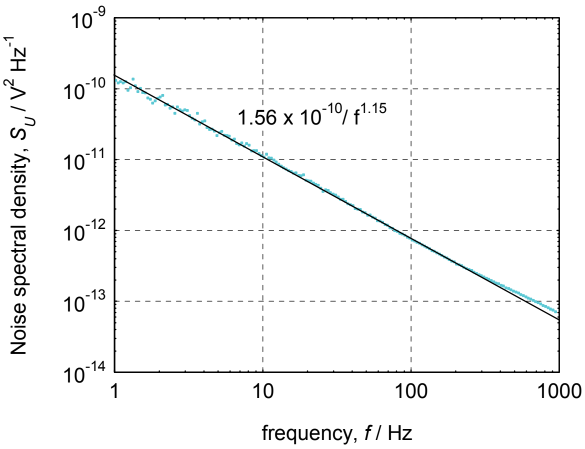

Fig. 7. Output-voltage noise spectral density S_U vs. frequency measured for silicon pressure sensor on a log-log scale. S_U is given by two components: the thermal noise spectral density $S_{UTh} = 1.0 \cdot 10^{-14}$ [V^2/Hz] and the 1/f noise spectral density $S_{U1/f} = 1.56 \cdot 10^{-10}/f^{1.15}$ [V^2/Hz].

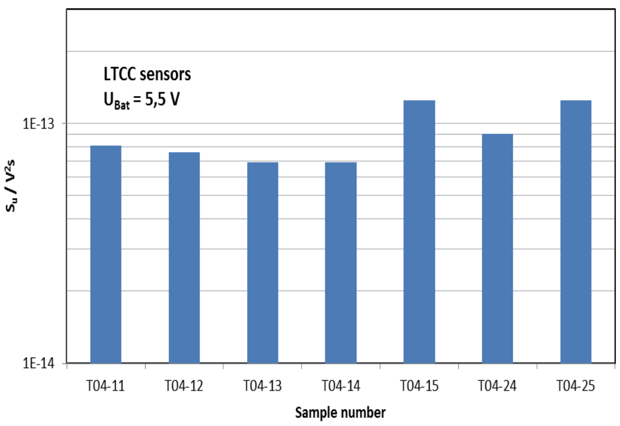

Fig. 8. Output-voltage noise spectral density $S_{U\,(1\,\text{Hz})}$ at a frequency of 1 Hz for all the samples of LTCC sensors (measured for Vs of 5.5 V).

Fig. 8 shows the values of the output-voltage noise spectral density $S_{U\,(1\,\text{Hz})}$ determined at a frequency of 1 Hz for all the samples of LTCC sensors (measured for Vs of 5.5 V). For all these samples the 1/f noise was dominant in the frequency range 1 to 1000 Hz. We can see that for all the samples the $S_{U\,(1\,\text{Hz})}$ value is in the range 0.7 to $1.2 \cdot 10^{-13}$ V^2/Hz, which is comparable with the value of $S_{U\,(1\,\text{Hz})}$ measured for sample CPS 04-24 considered in the calculation above. Thus the resolution is about 0.02 mbar for all the LTCC sensors.

2.4 Low-Frequency Noise vs. Pressure

The influence of the pressure load on the low-frequency noise level was studied for both the LTCC-based CPSs and the silicon pressure sensors. The dependencies of the spectral density of the output-voltage fluctuation on the frequency (applied voltage 5.5 V) are shown in Figs. 9 and 10 for a random CPS sample and the silicon sensor, re-

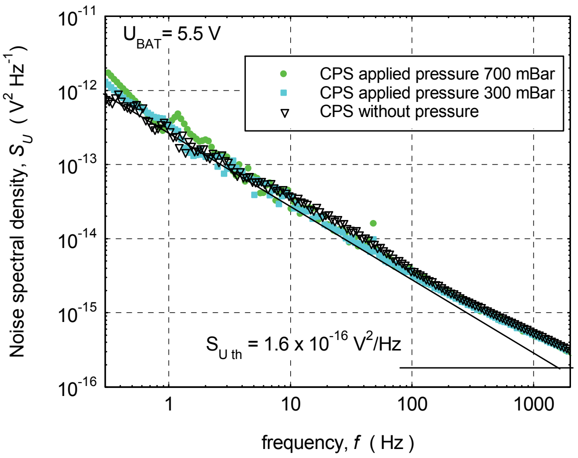

Fig. 9. Output-voltage noise spectral density S_U vs. frequency measured for the LTCC-based pressure sensor (on a log-log scale) without the pressure load and under overload pressures of 300 mbar and 700 mbar.

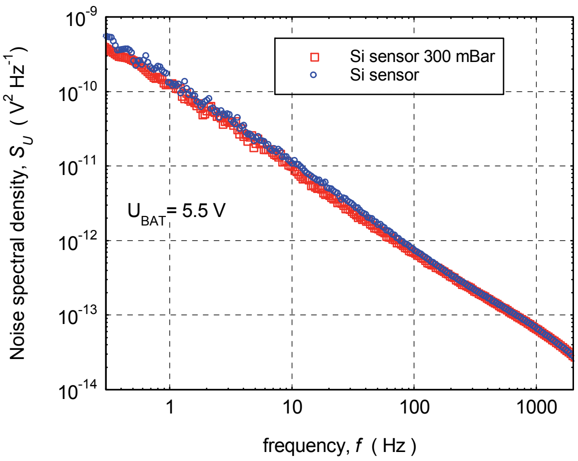

Fig. 10. Output-voltage noise spectral density S_U vs. frequency measured for the silicon pressure sensor (on a log-log scale) without the pressure load and under the overload pressure of 300 mBar.

spectively. These dependencies were measured without the pressure load and under two overload pressures: a pressure of 300 mbar was used for both CPs and the silicon sensor, and the pressure of 700 mbar was only applied to the CPS.

From Figs. 9 and 10 it follows that neither the LTCC-based CPSs' nor the silicon sensor's noise characteristics are influenced directly by the pressure load. So the sensor resolution does not change with the increased pressure, even if the overpressure is applied to the sensor.

3. Conclusions

The characterization tests and the noise analyses showed that a comparable resolution can be achieved for the piezoresistive LTCC-based CPS and the silicon pressure sensor. The measurements in the pressure range -5 to +5 mbar with a 0.5-mbar step showed that there was no significant difference between the sensors' output errors for the CPSs and the silicon sensors. For both sensors the deviation between the pressure measured at the sensor output and the applied pressure from the controller was less than 0.1 mbar.

The output-voltage noise measurements of the selected samples for both types of sensors (at a Vs of 5.5 V) showed the noise of the output voltage of the CPSs to be lower than 1 µV, while the value obtained for the silicon sensor was above 26 µV. Considering the typical sensitivity of the CPSs of 14 µV/V/mbar and the sensitivity of 65 µV/V/mbar for silicon sensors we calculated a resolution of about 0.02 mbar for the CPS and 0.08 mbar for the silicon sensor.

The low-frequency noise measurements showed that neither the LTCC-based nor the silicon-sensor noise characteristics are influenced directly by the pressure loads.

Taking into account the limited accuracy of the measurements under the pressure loads these results confirmed that the resolution of the LTCC-based CPS is at least comparable to that of the silicon sensor.

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