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Sensors and Actuators A 123–124 (2005) 234–239
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Capacitive pressure sensor in post-processing on LTCC substrates

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Received 13 September 2004; received in revised form 24 January 2005; accepted 29 April 2005
Available online 20 June 2005

Abstract

A capacitive pressure sensor was realized by means of a post-processing step on a low temperature co-fired ceramics (LTCC) substrate. The new sensor fabrication technology allows for integration of the sensor with interface circuitry and possibly also wireless transmission circuits on LTCC substrates to realize a truly autonomous sensor unit. A special feature of this sensor technology is the flush surface. The article describes the design considerations, and compares experimental data to the theoretical design. Special point of attention is the long-term behaviour of the soldering joint. Various design variants have been evaluated considering reproducibility and creep behaviour.

Keywords: LTCC; Pressure sensor; Capacitive; Creep; Soldering; Autonomous sensor

1. Introduction

Silicon is commonly used for commercial pressure sensors [1,2]. Of course this material also allows for integration of interfacing and other electronics on the same substrate. However, due to the high start-up costs, this technology is only suitable for high volume applications.

We present a new technology for the fabrication of a pressure sensor that is suitable for medium- and low-volume applications. This pressure sensor furthermore has a flat sensor surface that makes it especially suitable for stress analysis in solid media.

LTCC technology is a readily available technology for the realization of complex electronic circuits. Additional to the features of standard thick-film technology it allows for the integration of interconnect, actives and passives inside the substrate, so creating a very compact way of packaging and interconnecting electronic components [3].

For the realization of autonomous sensor units, i.e. sensors combined with the required interface electronics and power supply, the integration of sensors on LTCC substrates would offer interesting prospects for the small- and medium-volume market [4].

2. Pressure sensor theory

Pressure sensors generally consist of a flexibly mounted plate. A pressure difference between both sides of the plate causes a deflection. For a circular plate the deflection [5] is given by Eq. (1)

$$w(r, p) = \frac{p(a^2 - r^2)}{64D} \tag{1}$$

w is the deflection (m), r the radius (m), p the pressure (Pa), a the radius of the plate (m), D the flexural rigidity (N).

The capacitance between the deflecting plate and an underlying fixed electrode given by Eq. (2)

$$C(p) = \int_0^d \frac{2\pi r\varepsilon}{\text{gap} - w(r, p)}\,\mathrm{d}r \tag{2}$$

C is the capacity (F), d the electrode radius (m), gap the distance between electrodes at $p = 0$ (m), ε the dielectric constant (F/m).

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doi:10.1016/j.sna.2005.04.026

Substitution of Eq. (1) in to (2) allows for numerical evaluation of the sensitivity of various configurations. This analysis was performed with the mathcad® software package. The design was optimised in order to give a maximum sensitivity over the desired pressure range. Optimisation for maximum capacity would give a very small gap. However, due to the hyperbolic nature of the relation between pressure and capacitance this would give a much smaller sensitivity for negative pressures then for positive pressures. Therefore the gap was chosen significantly larger then the maximum deflection. Considering all these constraints the sensor was decided to have a diameter of 5 mm, a plate thickness of 200 μm and a gap of 10 μm.

The inner electrode was chosen 3 mm. This is significantly smaller then the plate diameter, because the edges do only marginally contribute to the sensor sensitivity. The edges do however give an offset in the capacity, which would have a negative effect on the final resolution.

For pressures ranging from −15 to 5 bar and a stainless steel plate this results in a capacity and deflection shown in Fig. 1.

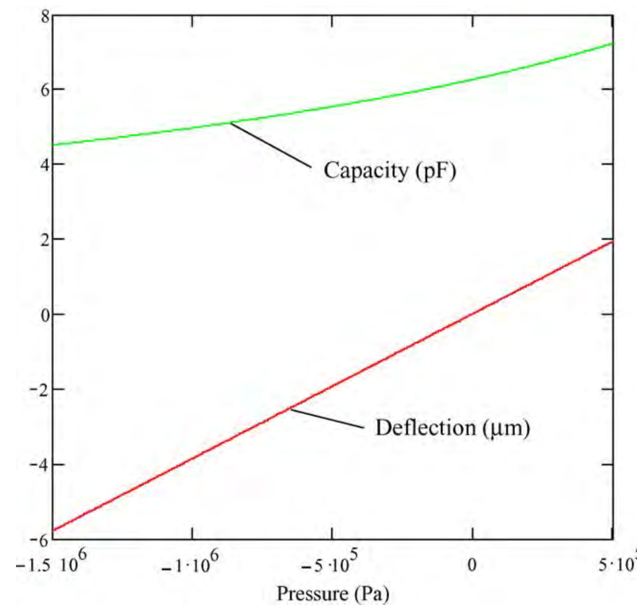

Fig. 1. Sensor capacity and centre deflection of the stainless steel plate as a function of pressure. Plate diameter and thickness are 5 mm and 200 μm, respectively. The gap is 10 μm.

3. Design and fabrication

Fig. 2 shows a schematic drawing of the sensor design. Apart from the calculated design with a diameter of 5 mm, samples with a diameter of 6 and 7 mm were also fabricated. These diameters allow to increase the sensitivity in case of experiments different plate materials or thicknesses.

LTCC substrates with test structures were obtained from Via Electronic GmbH [3], printing, lamination and firing parameters have been changed to achieve flat substrates with minimum height variation on the thick film patterns.

A ring of solder has initially been chosen as an interconnection to stay compatible with standard electronics manufacturing processes. A flip chip bonding process has been used to mount the (laser-cut) plates on the substrates (Fig. 3). By using a flip chip bonder accurate alignment can be achieved and an off-set in z-direction can be maintained

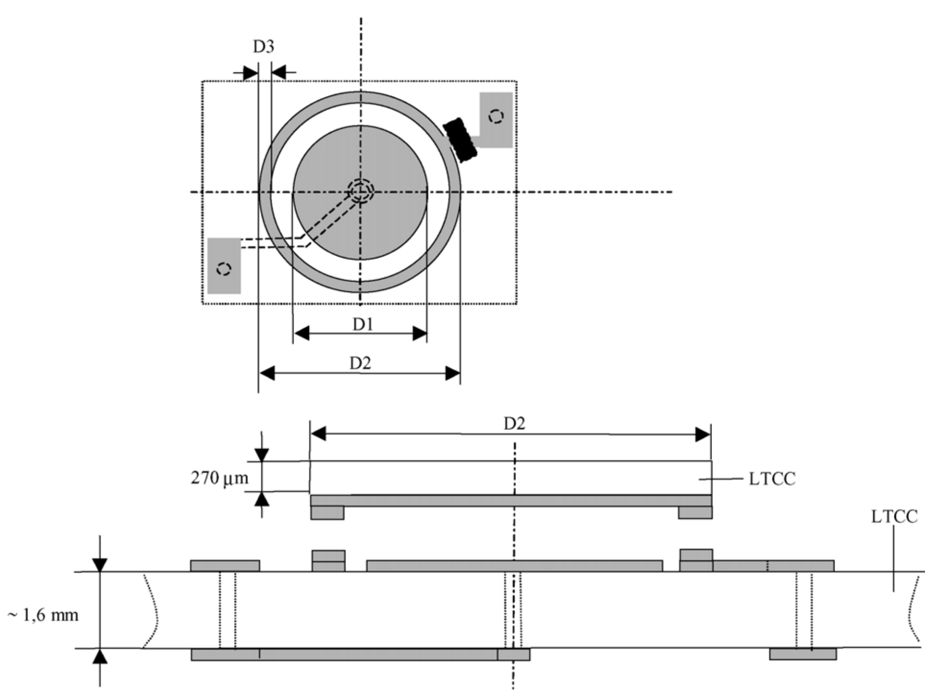

Fig. 2. The design of the sensor. D1 = 3mm, D2 = 5.8 mm and D3 = 0.4 mm.

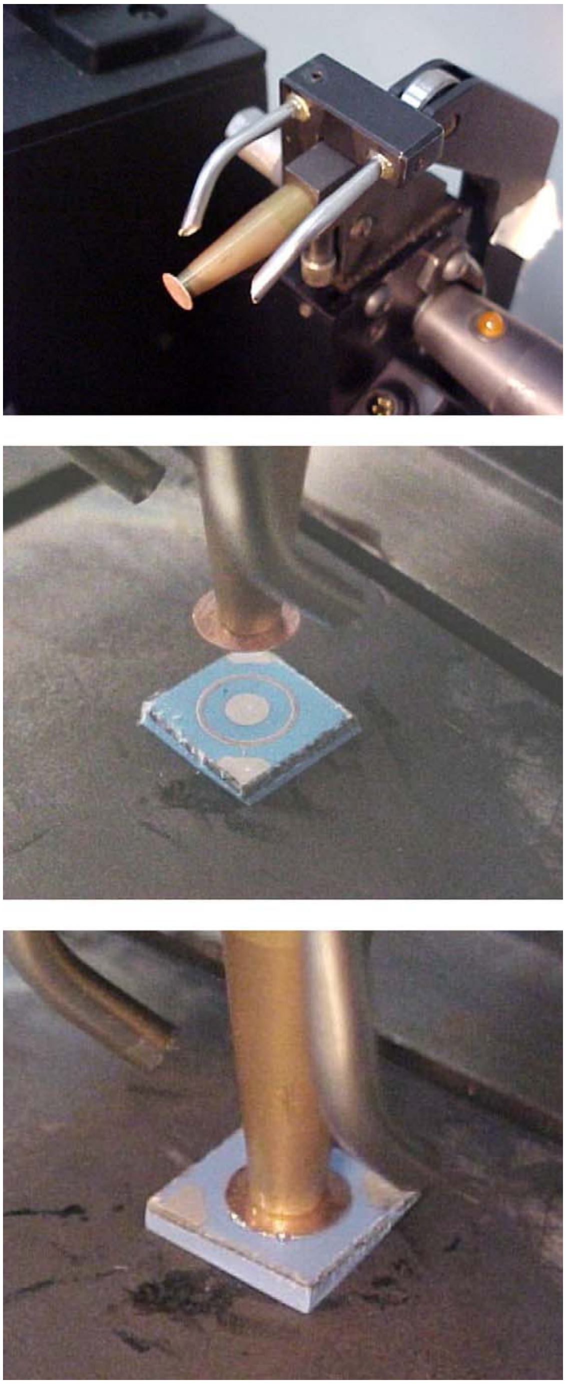

Fig. 3. The flip chip bonding process allows for accurate alignment and maintaining a gap during soldering.

during soldering. This technique works for gaps as low as 50 μm. For the 10 μm gaps that were necessary for this design, metal spacers were used.

The solder material has been applied by screen-printing or by placing preforms. Heat was applied from the top by the tool that holds the plate and from the bottom by a heating plate. During the soldering operation the temperature difference between the plate and the substrate did not exceed 10 °C.

Widely used SnPb37 solder has been used to first test the sensor principle and to develop the process. SnAg3Cu0.5 has been investigated as a lead-free alternative. SnAgCu alloys are at the moment the most important lead-free candidates for the electronics industry and exhibit a higher resistance to creep compared to SnPb solders [6]. The AuSn20 alloy is selected because it has appropriate mechanical properties and a melting temperature at 278 °C [7]. This high melting temperature allows reflow soldering of additional components without re-melting the sensor interconnection. With this method various plate materials were mounted. The materials used are summarized in Table 1. Considerations for the choice of the plate material are: compatibility with the soldering process, Young's modulus and the thermal expansion coefficient.

4. Experimental

The test samples were mounted in a test cell, for pressure characterization. The setup allowed pressurizing the sensors up to 5 bar by means of compressed air.

The capacitance of the sensors in the pressurized setup was measured with a specially designed electronic circuit with a resolution of 0.001 pF. For the characterization of sensor stability, the sensor was connected to an Agilent 4263B LCR meter. Special care was taken to the shielding and earth connections, in order to reduce the influence of parasitic capacitance. The LCR meter was connected to a PC to be able to perform periodic measurements over long intervals.

5. Results and discussion

5.1. Height variation on substrates

The metal rings on the substrates from the supplier showed height variations as large as a few micrometers. This is acceptable for the realization of functional sensor. The variation does imply the need for calibration of the sensors though.

5.2. Copper plates

Initial experiments were performed with copper plates and a traditional SnPb soldering process. This well-known process allowed optimisation of the mounting procedure with the flip-chip bonder. Fig. 4 shows some finished test samples with copper cover plates.

Sensitivity of the copper samples was according to Eq. (2) for the SnPb soldering process. For the SnAgCu soldering process however, the sensitivity of the copper samples was much lower. This is believed to be caused by the mismatch in thermal expansion coefficient between the copper plates and the LTCC substrates. The mismatch causes the plate to be 'stretched' after cooling, which results in a stiffer structure. The mismatch is of minor influence for the SnPb soldering process because of the lower temperature for this process,

Table 1
Summary of the types of samples that were fabricated and tested

Plate material	Young's modulus (GPa)	Coefficient thermal expansion (ppm/K)	Thickness (μm)	Diameter (mm)	Solder alloy
Copper	124	17	195	5.8, 6.8	SnPb37, SnAg3Cu0.5
Stainless steel (Ni–Au plated)	200	10	205	5.8	SnAg3Cu0.5, AuSn20
LTCC with thick film (Ag–Pd)	100	5.8	270	5.8	SnAg3Cu0.5

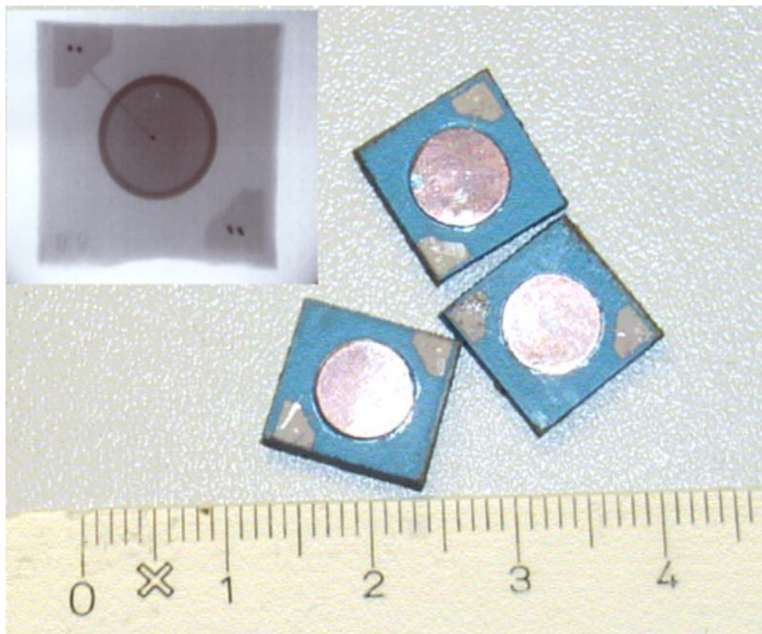

Fig. 4. Realised samples with a 6.8 mm copper plate. The corner triangles are soldering pads for connecting wires. The insert shows an X-ray image of the same structure.

and because of the weaker soldering bond, which allows the stress to relax after cooling down.

The SnPb process is not suitable for pressure sensors because of the considerable creep of this joint, which causes unstable transient sensor behaviour.

5.3. LTCC plates soldered with SnAgCu

LTCC was expected to be the material of preference for the pressure sensors because of the perfectly matched material's properties with the underlying substrate. Transient behaviour of these sensors (Fig. 5) was poor however. It can be seen that the creep over a period of 2 weeks corresponds to a pressure sensitivity for about 2.5 bar. This in spite of the improved resistance to creep of SnAgCu compared to SnPb. Part of this creep is likely to occur in the Ag–Pd layer that is fired on the LTCC plates.

5.4. Gold plated stainless steel plates

Stainless steel plates were plated with a nickel barrier and gold wetting layer in order to allow soldering with AuSn20. The stainless steel used had a reasonable match with LTCC for thermal expansion. Fig. 6 shows the response of such sensors to a staircase shaped pressure profile. The stability was better then 6% full scale when exposed to 5 bar (the maximum pressure) over a period of 2 weeks. The response of the sensors is slow (typically minutes) where one would

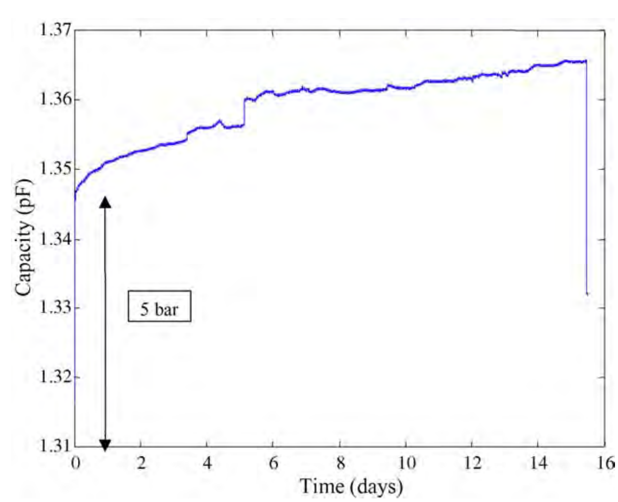

Fig. 5. Sensor configuration with the LTCC plate and SnAg3Cu0.5 solder showing creep behaviour. The jump after 5.5 days is considered to be an external artifact (movement of connection wire). The arrow on the graph corresponds to the response to a 5 bar pressure variation.

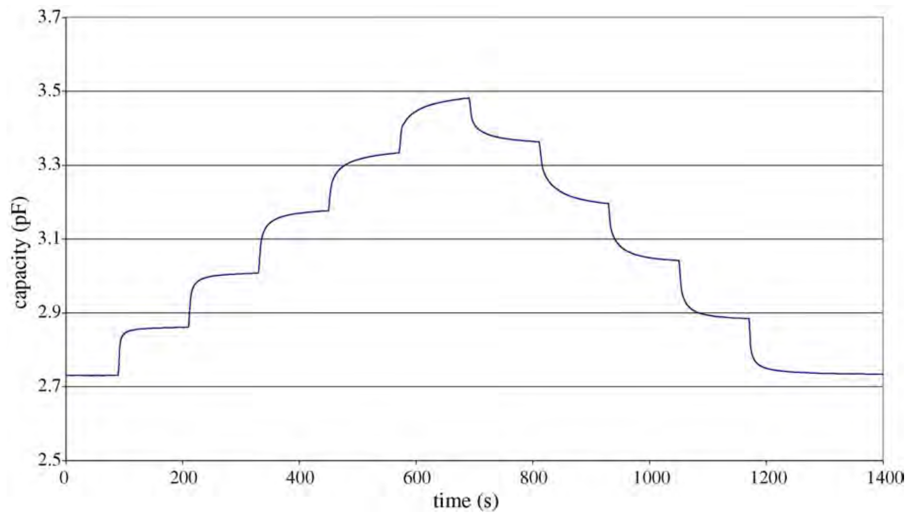

Fig. 6. Response of the 5 mm stainless steel AuSn20 soldered pressure sensor on a staircase shaped pressure profiles. Pressure varies from 0 to 5 bar with steps of 1 bar.

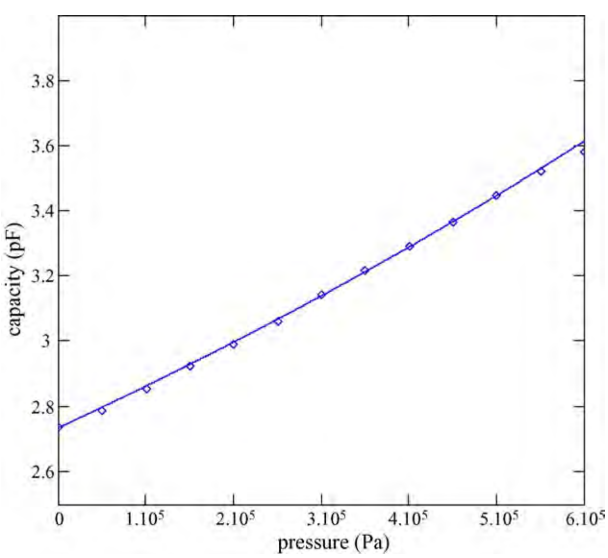

Fig. 7. Sensitivity of the 5 mm stainless steel AuSn20 soldered pressure sensor. Experimental data (diamonds) together with the simulations (continuous line).

expect an instantaneous response to a pressure step. This phenomenon can be caused by is not yet understood and is subject of a further investigation.

Fig. 7 shows the sensitivity of the AuSn20 soldered stainless steel pressure sensor. Due to the 10 μm gap (Fig. 1) and the small centre electrode, the sensitivity is sufficiently linear to give a good sensitivity of the complete sensing range. The remaining non-linearity will be compensated in the digital electronics that will in the future be integrated with the sensor.

6. Conclusions

We successfully integrated a pressure sensor on an LTCC substrate. The use of the LTCC substrate allows for compact integration with interface-electronics in order to create an autonomous sensor. A special feature of this technology is the flush surface. This is especially advantageous for use in material's stress analysis, where the sensor is incorporated in a material to measure tensile and compressive stresses.

The configuration with the Ni–Au plated stainless plate and the AuSn20 solder appeared to be the most promising. The AuSn20 solder is sufficiently strong for the soldering of the deflecting plates on the LTCC substrates. The sensitivity of the sensors is in good agreement with the deflecting plate theory.

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Biographies

M.G.H. Meijerink has an MSc in electrical engineering from Twente University, The Netherlands and a PhD in microtechnology from the University of Neuchâtel, Switzerland. He currently works as a project leader at TNO in The Netherlands. Dr. Meijerink's main activity is the application of sensory systems for demanding applications. Therefore he is interested in a wide range of sensor technologies.

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