

Structuration and Fabrication of Sensors Based on LTCC (Low Temperature Co-fired Ceramic) Technology

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Abstract

The purpose of this paper is to demonstrate sensors and structures fabricated using the LTCC technology, which has been addressed and employed increasingly as a smart packaging approach for several applications. The focus will be on inclination and cantilever force sensors and micro-fluidic structures. Motivation for selection of LTCC for these applications in addition to fabrication and structuring of the devices will be explained in details. TGA (thermo-gravimetric analysis), dilatometer analysis, SEM (scanning electron microscopy), electronic equipment for measuring sensor performance will be extensively used for explanation of the results. It will also be shown that, compared to classical thick-film technology on alumina, LTCC allows a considerable increase in sensitivity, and is therefore better suited for the sensing of minute forces and pressures.

Keywords: LTCC, sensors, sacrificial layers, micro-fluidic devices

1 Introduction

LTCC (low temperature co-fired ceramic) technology is based glass-ceramic sheets of varying thickness (30-350 μm) prepared by tape casting [1,2]. These sheets are then screen-printed with different thick-film compositions to provide conductor lines and passive electronic components such as, resistors, capacitors, etc. Finally, the consecutive layers forming a circuit are laminated and fired, resulting in a 3-D electronic module.

LTCC glass-ceramic initially consists of a glass + inorganic filler mixture. During firing, the softening glass wets and rearranges the filler particles, ending up with a dense material. The exact composition of the glass and the filler depends on the desired processing temperature and final properties [2,3]. "Standard" LTCC materials systems are designed to fire in the 850 to 900 $^{\circ}\text{C}$ range and comprise adapted thick-film materials in order to reliably achieve complex circuits [3]. Furthermore, the advantages provided by low-temperature processing ($<900^{\circ}\text{C}$) and simultaneous firing of the LTCC with the thick-film materials are compounded by the possibility to fabricate intricate 3-D LTCC structures. This makes LTCC a very promising platform for various sensor, actuator and fluidics applications [4,5].

Therefore the focus of this study is to give an insight to the fabrication of sensors using this technology, with a focus on inclination and force sensors and micro-fluidic structures. The methods used for the analysis of the materials and fabricated devices are TGA (thermo-gravimetric analysis), dilatometry, SEM (scanning electron microscopy) and electronic equipment for measuring sensor performance.

2 Experimental

The overall list of materials used for fabrication of the devices is given in Table 1. Functional element of all of these devices is the resistors with special functions: positive temperature coefficient or piezoresistor TFR's (thick-film resistor). Dimension in z-direction refer to the substrate (thickness), where the sensing element or resistor is screen-printed.

Processing steps for the devices are the same; LTCC tapes, which have an excellent plasticity providing an ease for handling and structuring prior to firing, are cut, screen-printed with thick-film components

(conductors, resistors), laminated and finally fired at 875 °C. Among the fabricated devices, only the force sensor is co-fired with the resistor, whereas the other two are post fired. The former treatment stands for firing of printed paste with the yet-unfired LTCC tape, whereas in the latter case the paste is screen-printed and fired on the already-fired LTCC.

Micro-fluidic structures are fabricated using a graphite powder-based sacrificial paste, which we have produced, to prevent sagging during firing. This type of defect is widely observed in closed structures such as membranes, channels, etc., unless the layers above the cavities are supported mechanically. The origin of sagging is due to the glass softening in the tape, which occurs over glass transition temperature, T_g . The developed sacrificial layer provides a mechanical support until the start of LTCC densification and then oxidized. The burn-out products are released through the porous LTCC surface. Both of these reactions; graphite burn out and LTCC densification, are related to processing parameters, material properties and affected by reaction kinetics. A more detailed explanation on this can be found in [6].

The sacrificial layer is prepared by mixing the graphite powder with an organic vehicle (binder-solvent-dispersant), which is then homogenized on a three-roll mill. The suspension is screen-printed on the LTCC layer and laminated with additional LTCC layer and fired. Following this initial firing, graphite powder is successfully oxidized and degassed, leaving behind a cavity, which has a uniform definition, without warpage or sagging.

3 Fabricated sensors

3.1 Inclination sensor

The working principle of the sensor is based on the heat loss on the PTC (positive coefficient temperature) resistor, which is screen-printed on the 100 μm -thick LTCC substrate. As it can be seen from the construction of the sensor (fig. 1.a, b), the heat loss on the resistor (hot spot) depends on the environment with which the resistor is in contact. Therefore, when there is no inclination, the bubble is directly under the resistor and so that the dissipated heat is reflected back to the resistor by the bubble surface (fig. 1.b). This provides the PTC resistor to retain its temperature. In case of inclination, the heat over the resistor is dissipated through the liquid, which reduces the temperature of the resistor. The critical parameters for the sensor's functioning can be listed as the thickness of the substrate, boiling temperature and surface tension of the liquid used and the operating parameters.

Selection of LTCC instead of widely used alumina is due to its thermal conductivity, which is approximately 2-3 W/m/K; around one tenth of that of alumina (27 W/m/K). This is a crucial parameter for the proposed hot spot method to work efficiently, by reducing the heat dissipation in the substrate. The performance of the sensor is shown in fig. 1.c. The sensitivity can be increased further by thinner substrates, which provide more direct and efficient heat source to fluid environment contact.

3.2 Millinewton force sensor

The purpose of this study is the replacement of the alumina-based beam material of the sensor, with LTCC. The major motives for such a change can be listed as: the ease and plasticity of LTCC, which gives design freedom, its lower elastic modulus and finer thickness compared to alumina (110 GPa [7] and 40 μm , respectively), which lead to increased deformation (strain) under applied force. The effect of the last two factors can be best explained by eq.1, which clearly shows the ratio of strains between LTCC and alumina. The ratio, which can reach up to 70 times theoretically, provides an improved sensor performance (eq. 2).

$$\varepsilon_{\text{LTCC}} / \varepsilon_{\text{Al}_2\text{O}_3} = (b_{\text{Al}_2\text{O}_3} \cdot h_{\text{Al}_2\text{O}_3}^2 \cdot E_{\text{Al}_2\text{O}_3}) / (b_{\text{LTCC}} \cdot h_{\text{LTCC}}^2 \cdot E_{\text{LTCC}}) \quad (1)$$

$$\text{Signal} = \varepsilon \cdot G_f \quad (2)$$

where ε , b , h , E , G_f are the strain, width, thickness, elastic modulus and gauge factor, respectively. One can see the schematized sketch of the sensor in fig. 2.a. Two active piezoresistors, which are screen-printed on the beam (fig. 2.b) and co-fired with a double-layer LTCC, are strained by the force applied. By definition of piezoresistivity, such a strain leads to a change in resistance of the piezoresistors, which is then measured by a Wheatstone bridge. The novelty of this sensor comes from the design, by which the strain imposed on the resistors (eq. 1) is increased. The preliminary results obtained by applying 400 mN force on the alumina

and LTCC-based sensors (three) are demonstrated in fig. 2.c. In spite of a thicker LTCC substrate used for this study (by 20%), a signal that is twice that of alumina beam is obtained as a result of a gain in E and b .

On-going study is focused on LTCC substrates with finer thickness and reduced deformation, the latter issue being a concern due to the differential shrinkage between the screen-printed pastes and the LTCC. Matching the shrinkage rates of the components, in addition to thinner substrates is believed to increase the sensitivity of the sensor remarkably.

3.3 Micro-fluidic Structures

Although LTCC technology provides means for building complex 3-D structures effectively, fabrication of micro-fluidic devices such as membranes, channels with fine dimensions is not always straight forward. Such structures tend to sag due to softening of glass in LTCC over T_g , which requires the loose ceramic structure to be supported mechanically.

Among a variety of methods to overcome this problem, we have used a self-produced carbon-black sacrificial paste. It is based on the graphite powders, which are blended with an organic vehicle that is then screen-printed on LTCC. The structure is laminated with additional LTCC layer and co-fired at 875 °C. The paste is oxidized at a temperature that is over the onset of LTCC densification temperature. The method, although being efficient, is strongly dependent on a number of parameters such as densification behavior of LTCC, particle size of the powder, processing conditions, etc. [6].

Membranes with a thickness of 40µm-thickness and a variety of diameters (7-18 mm) are fabricated, which are promising for different applications such as micro-fluidic platforms, pressure sensing, etc. Cross-section of these membranes at different scales and a finalized sensor with two printed-TFR's, inlet and outlet ports for fluidic applications are shown in fig. 3.

4 Conclusions

Sensors and micro-fluidic structures, which are fabricated using the LTCC technology, have been demonstrated. The performances shown are of preliminary results, which are expected to be improved by reducing the materials incompatibility of co-fired materials such as differential shrinkage, chemical interaction, etc. Plasticity of tapes providing ease of fabrication of complex 3-D structures, integration of thick-film technology leading to high density packaging, hermeticity, thermal and chemical inertness of fired tapes, etc. make the technology a reliable and efficient alternative to the widely-used alumina.

References

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Table 1. Materials Used for Device Fabrication.

Device	LTCC materials / Thick-film components			Dimensions (mm) x : y (diameter) : z
	LTCC tape	Termination	Resistor	
Inclination sensor	Heraeus (CT 2000)	DuPont 5744 (Au)	ESL 2612, PTC (Positive Temperature Coefficient)	14 : 0.11
Force sensor	DuPont (951 series)	DuPont 9473 (Ag/Pd-modified)	DuPont 2041 (Piezoresistor)	15 : 3 : 0.13
Micro-fluidic structures	DuPont (951 series)	DuPont 6146 (Ag/Pd)	ESL 2612, PTC DuPont 2041 (Piezoresistor)	10-18 : 0.04

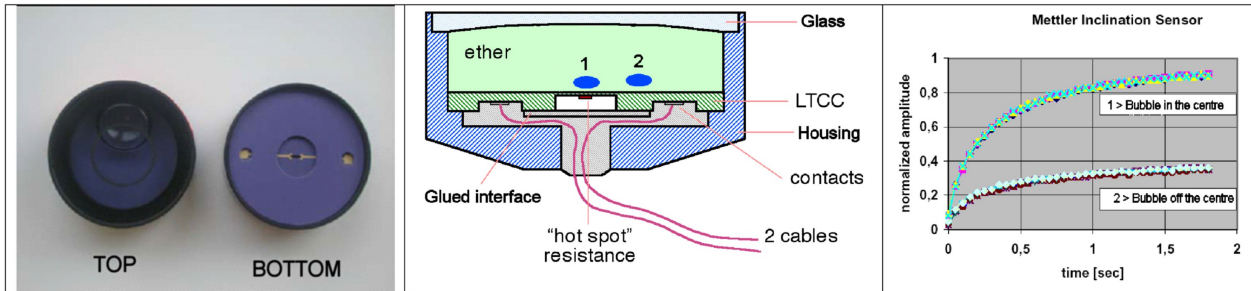


Fig. 1.a. Fabricated sensor, b. Sketch of the sensor, c. Test results in case of inclination angle, $\alpha = 0$ (position 1) and $\alpha \neq 0$.

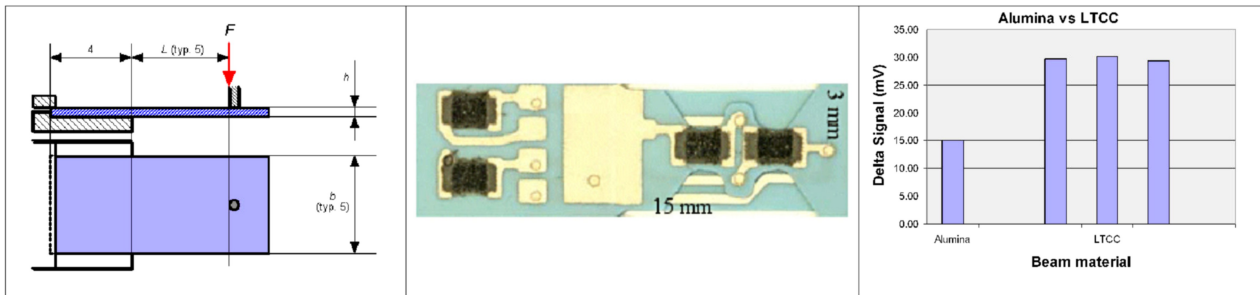


Fig. 2.a. Side / top views, b. Fabricated LTCC-beam, c. Preliminary results of Alumina vs. LTCC.

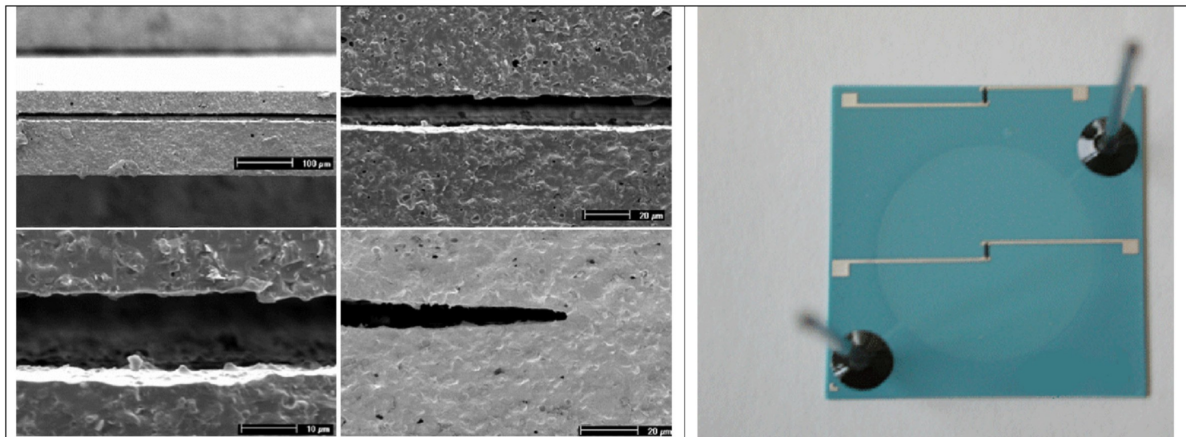


Fig. 3.a. Cross-sections of sag-free, well-integrated membrane, b. Micro-fluidic sensor.