Fabrication and Characterization of LTCC-based Millinewton Force Sensor: Influence of Design and Materials Compatibility on Device Performance

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Abstract

LTCC (low temperature co-fired ceramic) technology has recently gained a remarkable application potential in sensors field. This can be ascribed to many advantages it offers: the ease of LTCC tape handling providing a great freedom in design and fabrication, feasible processing conditions bringing down the costs, excellent thermal and chemical resistance, and combination of electrical and mechanical functions in a reliable hermetic system. In scope of this, fabrication of an LTCC-based millinewton force sensor is introduced in this paper. Processing steps, design and electrical performance of the sensor is explained in details. The results are compared to the previously-fabricated sensor that is based on alumina. It is shown that the sensitivity of the sensor is significantly improved in the first attempts, by replacing the alumina beam with LTCC. In a separate section, LTCC-materials incompatibility issues and their effects on the sensitivity of the sensor are discussed. The tools of the study are SEM (scanning electron microscopy), dilatometry and electronics for characterization of the sensor.

Introduction

LTCC technology is based on utilization of LTCC sheets, which are co-fired with screen-printed thick-film materials (conductors, resistors, etc.) below 900 °C [1]. The sheets are composed of ceramic filler, which is mixed with glass load at varying quantities. This mixture is blended with an organic vehicle to form slurry, that is cast on carrier films (mylar sheets). The thickness (30-350 µm) and the plasticity of the tapes provide an ease and freedom for design, handling and fabrication of various 3-D structures [1]. This advantage comes along with additional benefits such as hermeticity and chemical inertness of the fired modules and high reliability that is attainable at low costs, making the technology ideal for sensor applications. The literature contains numerous studies describing performance of sensors, which are fabricated using LTCC [2-5]. The physical quantities such as force, flow, heat, pressure are detected by elegant methods using this technology.

In this paper, we demonstrate a novel millinewton force sensor, which is integrated with an LTCC-based beam as an alternative to the alumina-based version. Force is measured by the resistance change of piezoresistors (piezoresistivity), which are screen-printed on the beam and strained by the applied force. The novelty of the sensor lies in the design concept of the beam, which is explained in details, in addition to the motivation for selection of LTCC as the beam material and performance comparison with the alumina-based version.

It is also observed that differential shrinkage between the co-fired LTCC and the conductor paste lead to beam deformation. Therefore the commercial conductor pastes are modified to shrinkage-match with the LTCC and reduce the deformation, which is discussed in a separate section. The tools of the study are SEM, dilatometry and electronics for micro-structural and electrical characterization of the sensor and components.

Theory

The working principle of the sensor is based on piezoresistive effect: the applied force, which deforms (strains) the beam of the sensor, is measured by resistivity change of the piezoresistors, those screen-printed on the beam [6]. The relation between the force-strain-signal (resistance change) is given in equations 1 and 2. The first equation clearly demonstrates the importance of the beam material in determining the extent of the signal: beams, with smaller elastic modulus, strain more and result in increased signal.

$E = \sigma / \varepsilon$ … (1)

Signal = $\varepsilon_{max} G_f$ or $(\Delta R / R) = (\Delta l / l) G_f$ … (2)

where E, σ, ε, G_f, R, l are the elastic modulus, stress, strain, gauge factor, resistance and length (size), respectively.

Apart from elastic modulus, thickness of the beam is also an important factor in determining the value of the signal. The relation between the maximum stress applied prior to fracture and the thickness of the beam is given by equation 3.

$\sigma_{max} = (6FL) / (bh^2)$ … (3)

where, F, L, b and h are the force, effective bending arm length, cantilever width and thickness of the beam, respectively. These parameters are shown in figure 1, which demonstrates the test jig for measurements.

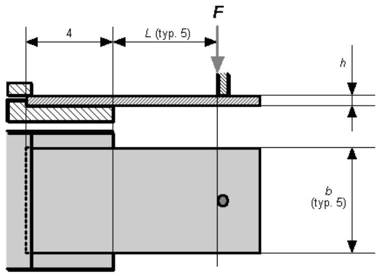

Figure 1. Schematized test jig (side and top views shown consecutively).

By using equation 1 in 3 and assuming the identical effective length (L) and applied forces, the strain ratio of two beam materials; LTCC and alumina, can be written as in equation 4. It is clearly seen that, the ratio of strains depends on the elastic modulus and the dimensions of the beam. In light of this relation, table 1 demonstrates the corresponding properties of the two materials. One can see that LTCC can strain up to 70 times of alumina theoretically. This can further be increased by a novel design, which we will be showing in the next section.

$\varepsilon_{LTCC} / \varepsilon_{Al2O3} = (b_{Al2O3} h^2_{Al2O3} E_{Al2O3}) / (b_{LTCC} h^2_{LTCC} E_{LTCC})$ ...(4)

Table 1. Mechanical Properties - Al_2O_3 vs LTCC

Properties	Kyocera A-476 Al_2O_3 (96%)	DuPont LTCC 951 (fired)
Elastic modulus (GPa)	330	152
Flexural strength (MPa)	310	320
Available thickness (mm)	0.25-1.00	0.04-0.21

Data extracted from technical data sheets [7, 8].

Experimental

The beam has dimensions of 15 mm x 3 mm x 0.18 mm (length x width x thickness) and fabricated using two layers (figure 2). The top and bottom layers are under tension and compression respectively. The top layer is ideally selected thinner in order to maximize the ratio between the compressive and tensile stress [9]. In order to increase the compressive stresses on the piezoresistors, a novel design is introduced by cutting out the tapes with a neck-region, where the piezoresistors are screen printed (figure 3).

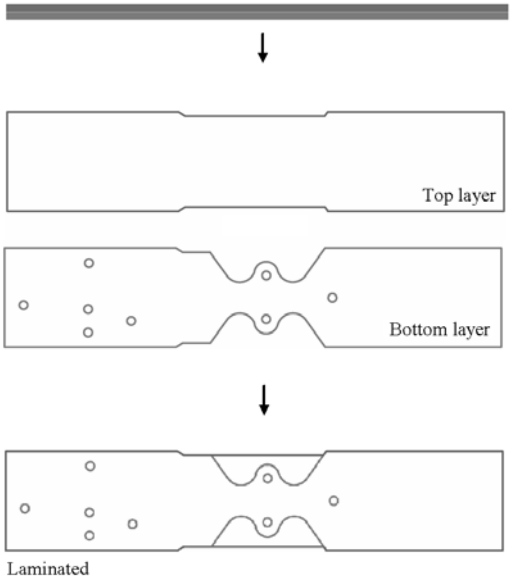

Figure 2. Top and bottom layers of the beam.

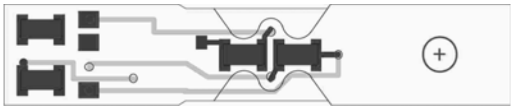

Figure 3. Layout of the top (gray lines indicating sandwiched conductors) and bottom (resistors) layers.

Throughout the whole study, DuPont-made, 951-series LTCC tapes are used in addition to Ag/Pd-based conductor and Ru-based piezoresistor thick-film material. Processing steps can be summarized as: tape cutting by laser, screen printing on top and bottom layers, lamination and firing at 875 °C in air. The whole structure is co-fired (figure 4) and then soldered onto the mechanical support (figure 5), which also carries electronic circuitry.

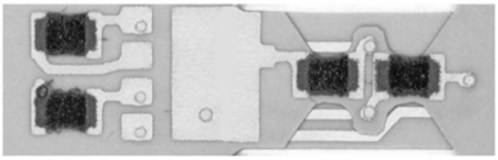

Figure 4. A completed LTCC beam.

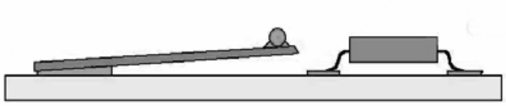

Figure 5. Profile of the beam on a base, with a centering ball on the top and the amplifying electronics on the side.

Discussions

Before elucidating with the performance of the sensor, it would be useful to highlight the importance of materials compatibility, especially between the LTCC and the conductor. The dilatometer analysis suggests that the Ag/Pd-based conductor (DuPont 9473) starts shrinking approximately 150 °C prior to LTCC (figure 6), which finally deforms of the co-fired beam. In order to reduce the extent of this deformation, we modified the commercial paste by adding glass-network promoting species such as SiO_2. It is observed that such a modification increased the onset of shrinkage temperature of the conductor by 130 °C, bringing it closer to that of LTCC (figure 6). Moreover, the overall shrinkage was reduced by 21%, avoiding the beam deformation effectively (figure 7).

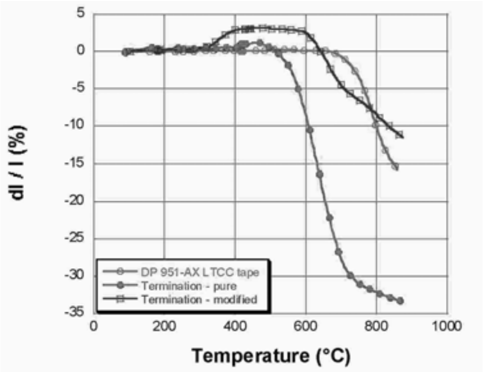

Figure 6. Profile of the beam on a base, with a centering ball on the top and the amplifying electronics on the side.

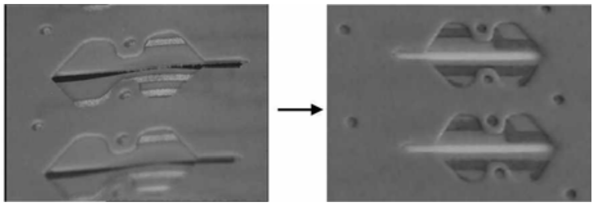

Figure 7. Reduced deformation on the beam (on the right) with the improved termination.

Preliminary SEM studies suggest a modification of the microstructure by SiO_2 addition, where the mobility of glass over T_g (glass transition temperature) is hindered by the silicate particles. This is thought to be the mechanism of reduced differential shrinkage between LTCC and the conductor, although the exact description is still being sought.

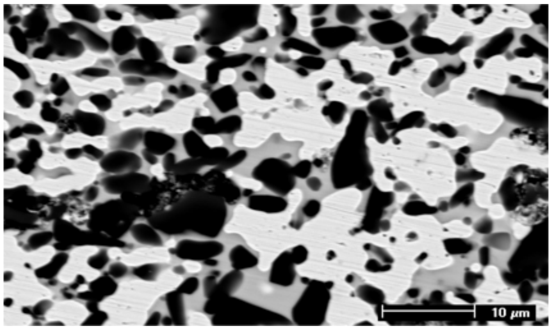

Figure 8. Microstructure of the modified conductor (pellet). White regions are Ag/Pd and grey regions are glass (Zn-Bi). Black particles on the whole matrix are silicate.

Results

Three different beams were tested: 250 µm-thick alumina, 180 and 290 µm-thick LTCC (fired thicknesses). The LTCC-based beams had a top/bottom layer configuration of green tapes at 110/110 and 110/250 µm thicknesses. Electrical characterization was made using Wheatstone bridge with two active resistors (half-bridge) and the difference between the offset and the actual voltage value was noted as the voltage change. Measurements were made by hanging weights on the beams in the 0-800 mN range. Figure 9 demonstrates the performance of the fabricated millinewton force sensors.

It is seen that an improvement of signal by 2 times is provided by replacing the alumina beam with LTCC. The second series of beams based on 110/110 configuration were observed to be deformed due to shrinkage mismatch of conductor with LTCC. This problem is solved with the modified paste, which is used in the 110/250 configuration. These letter beams reach the sensitivity of 110/110 configuration in spite of an increased thickness (by 60%).

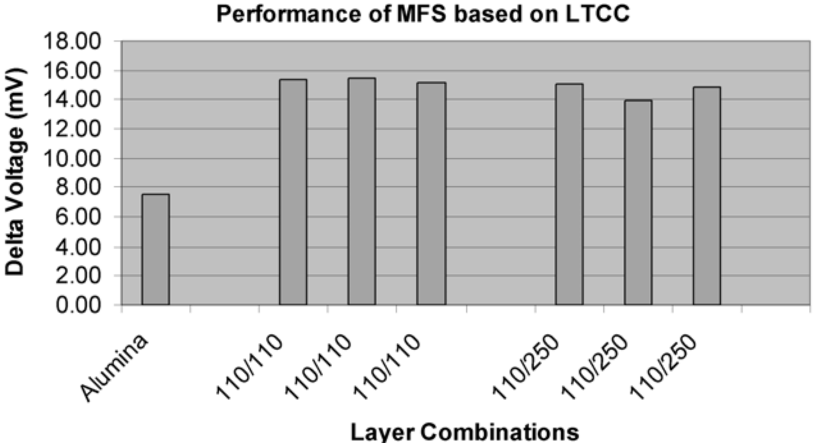

Figure 9. Sensitivity of alumina and LTCC-based sensors under 400mN.
X-axis shows the layers configuration of top/bottom layer.

Conclusions

Fabrication of a millinewton force sensor is introduced using the LTCC technology. The new sensor replaces the alumina-based beam of the previous sensor with LTCC, thus improving the sensitivity by more than 100% in the first attempt. The novelty of the sensor lies in the narrow neck-section, where the piezoresistors are screen-printed. Increased strain is obtained in this region upon applied force, providing an increased sensitivity. Further improvement of the signal is strongly dependent on the quality of the beams (flatness, deformation-free), thickness of the LTCC sheets and the materials compatibility. Results suggest that beams with reduced deformation reach a sensitivity value that is equal to much thinner beams with increased deformation.

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