MILLINEWTON FORCE SENSOR BASED ON LOW TEMPERATURE CO-FIRED CERAMIC (LTCC) TECHNOLOGY

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ABSTRACT

Fabrication of a millinewton force sensor, which is based on LTCC technology as an alternative to the widely used alumina (Al_2O_3) is described. The new sensor, integrated with piezoresistor thick-film, has shown an increase in the sensitivity by two times compared to the alumina-based version in the first attempt. This is ascribed to the smaller elastic modulus and finer substrate thickness attainable by LTCC. Moreover design flexibility is also an important factor, which contributes to the increased sensitivity of the sensor. It is strongly expected that the device performance can further be improved, by modifying the co-fired LTCC components such as LTCC tape and the thick-film terminations.

1. INTRODUCTION

Millinewton force sensor is a direct and effective means of measuring applied forces. One of the most common methods for measuring force in this range is utilization of piezoresistor thick-film resistors (TFR), which are printed on deformable substrates [1]. The force, which strains the film, is measured by a change in resistivity. This relation is expressed by gauge factor (Gf), which is known as

$$G_f = (\Delta R / R) / (\Delta l / l) \ldots (1)$$

where, ($\Delta R/R$) and ($\Delta l/l$) are the change of resistance and dimension (strain), respectively. The origin of this change arises from the alteration of micro-structural dimensions in the resistor [2]. The resistivity change is measured by the voltage output of a Wheatstone bridge. The amount of deformation (strain) is the key parameter as it determines the obtained signal directly according to

$$\text{Signal} = \varepsilon_{max} G_f \ldots (2)$$

where, ε_{max} is the maximum strain and G_f is the gauge factor. The substrate, which carries the screen-printed TFR, plays an important role in the sensitivity of the sensor. Intrinsic material properties such as elastic modulus, flexural strength, etc. influence the amount of strain imposed on the TFR. Moreover design flexibility can increase the overall device performance, as an independent parameter from material properties.

The standard substrate employed in thick-film technology is alumina [1]. The mechanical, physical and chemical properties of this material have been well known so that compatible electronic components are developed to be used with alumina. However increasing demands for smart packaging, increased and reliable functionality in reduced volumes at low prices have been the major motivation for development of new materials as alternative to existing substrate solutions.

LTCC technology has recently been used in the sensors domain for versatile applications [3, 4]. The technology is based on LTCC sheets (green tapes), which can be co-fired (simultaneous firing) with electronic passive components such as thick-film terminations, resistors (TFR), capacitors, etc., below 900°C. The tapes are available at varying thicknesses (50-250µm), which can be stacked up to 80 layers following screen-printing [5]. One of the most interesting features of the technology is the ease of handling of tapes (punching, cutting by laser, etc.) and the possibility for fabrication of complex 3-D structures.

Therefore the motivation of this study is to use the LTCC substrate to improve the performance of the millinewton sensor based on alumina [6]. The motive for utilization of LTCC will be demonstrated by comparing mechanical and physical properties of the substrate materials. This will be followed by explanation of fabrication techniques and demonstration of fabricated sensors. The results obtained by both substrate materials will be briefly compared and further possibilities for improved electrical performance using LTCC will be discussed. The methods of the study are push-test machine for measuring substrate strength, measurement set-up for applying force on the millinewton sensor that is connected to the electronic instrumentation and PC system for measuring force (by resistivity change).

2. CONCEPT AND COMPARISON OF MILLINEWTON FORCE SENSORS

Millinewton force sensors based on piezoresistive measurement principle have been widely used due to their low cost and reliability [7]. The figure of merit for these sensors is the elastic strain, which is desired to be maximized for increased sensor response. Therefore substrates with low elastic modulus are ideal in addition to other requirements such as high strength and compatibility with thick-films [7]. The comparison between the mechanical properties of alumina (96% pure) and LTCC substrates is demonstrated in table 1. In light of these properties, selection of LTCC as an alternative to alumina can be summarized as in the following;

First of all, higher strain is attainable with LTCC due to lower elastic modulus, E, a term which sets the relation between the stress and strain according to

$$E = \sigma / \varepsilon \ldots (3)$$

where, σ and ε denote stress and strain, respectively. Secondly, substrates with finer thicknesses using LTCC provide increased deflection, which can be visualized in the schematized test jig shown in figure 1. According to the design, maximum stress, σ_{max}, is calculated by

$$\sigma_{max} = (6FL) / (bh^2) \ldots (4)$$

where, F is the applied force, L is the effective bending arm length, b is the cantilever width and h is the cantilever (substrate) thickness. From (3) and (4), one can write

$$\varepsilon = (6FL) / (bh^2)E \ldots (5)$$

which can be further simplified by using identical parameters, except thickness and re-written in terms of strain ratios of two substrates as

$$\varepsilon_{LTCC} / \varepsilon_{Al2O3} = (h^2_{Al2O3}E_{Al2O3}) / (h^2_{LTCC}E_{LTCC}) \ldots (6)$$

This result clearly demonstrates that LTCC substrate, which is half as thick as alumina, can strain up to eight times that of alumina, which basically summarizes the motivation of this study.

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 [8, 9].

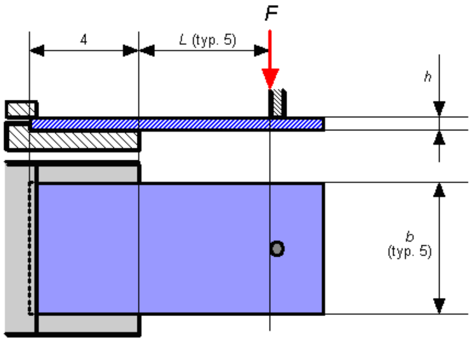

Figure 1. Schematized test jig (side and top views shown consecutively).

2.1 Alumina-based force sensor

The design of alumina-based millinewton produced at LPM is demonstrated in figure 2 [7]. The side and top views show the soldered alumina cantilever beam and screen-printed films on the substrate, respectively. A finalized product is shown in figure 3, where one can see the force centring ball and measuring resistors. Resistivity change is measured by a Wheatstone bridge (figure 4).

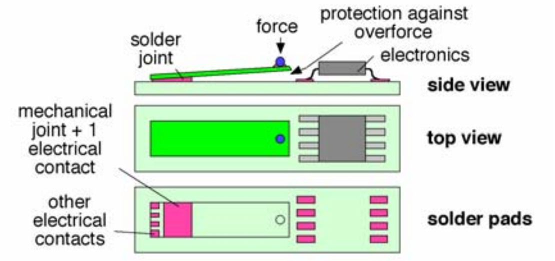

Figure 2. Design of the alumina-based force sensor.

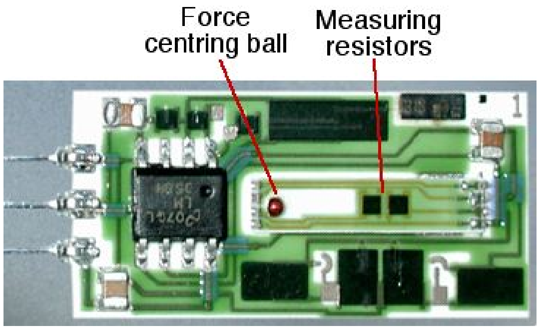

Figure 3. Finalized product.

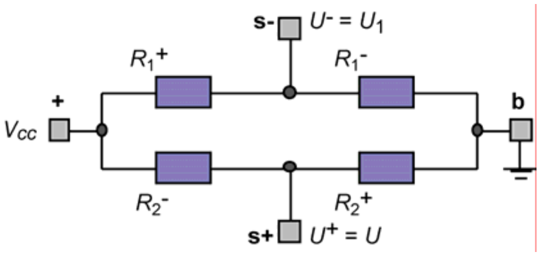

Figure 4. Wheatstone bridge to measure change of resistivity.

2.2 LTCC-based force sensor

The main difference introduced by replacing the alumina-based millinewton force sensor by LTCC is the new design. According to the new concept, there are two layers (figure 5), which can be selected from a variety of LTCC tape thicknesses (each layer being 110µm for this study). Top layer, which is under tension, is ideally selected thicker compared to the bottom layer in order to avoid crack initiation during cutting the fired pieces by laser and crack growth under applied force. On the other hand, the bottom layer is under compression, which eliminates the possibility of crack propagation. This facilitates integration of a thinner substrate, which can strain more, resulting in an increased signal upon exerted stress. The device performance can be further improved by selecting the design shown in figure 6, where the piezoresistors are screen-printed on the neck portion of the bottom layer, where the stresses are maximized.

The experimental steps are screen-printing terminations on each layer and lamination at 25MPa by a uniaxial press that is heated to 70°C. This is followed by firing the samples at 875°C for 25 minutes, in air. Piezoresistors and conductors for electrical vias are post-fired (on the fired LTCC sheet) in a 45 minute-firing profile with a peak temperature of 850°C. Finally the individual cantilever beams are scored by laser from the 10x2 piece (figure 7). The top layer is slightly thinner in the neck region of the beam, in order to avoid crack formation during scoring. The finalized millinewton force sensor can be seen in figure 8-d.

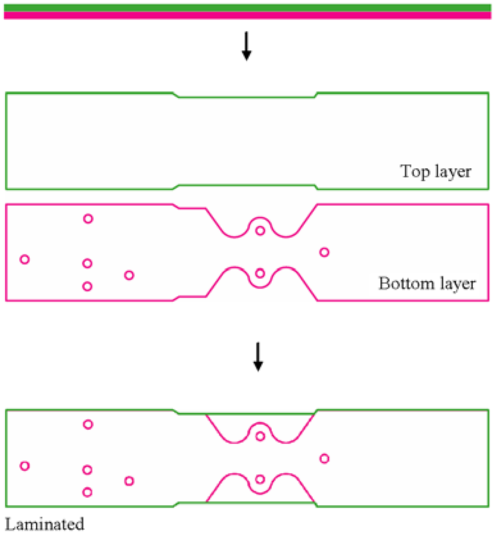

Figure 5. Individual layers of the sensor based on LTCC (side and top views).

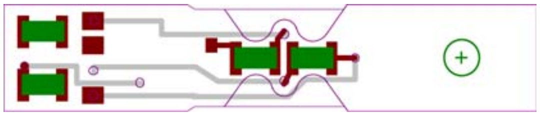

Figure 6. Laminated sensor sketch with piezoresistors. Gray lines are terminations, which are sandwiched between two LTCC layers.

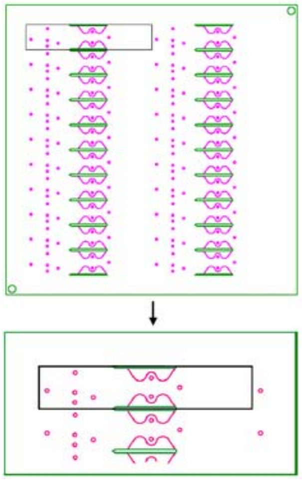

Figure 7. Scored cantilever beam after firing.

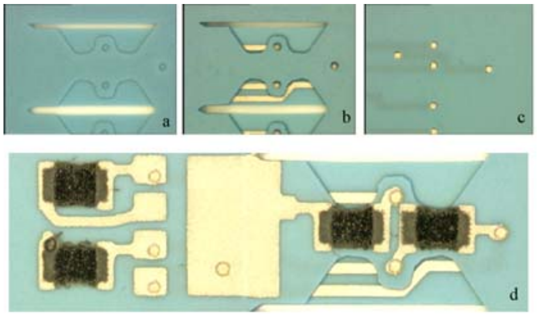

Figure 8.a. un-scored & un-printed beam, **b.** sandwiched conductor, **c.** filled via and **d.** scored sensor with, terminations and piezoresistors printed and vias filled.

2.3 Measurement with the new sensor and comparison of the sensitivity of sensors

Measurement with the LTCC-based millinewton force sensor is made under an applied force (suspended weights) in the range of 0-800mN. The sensor response is measured at two different supply voltages; 5 and 10V (figure 9). It is seen that the signal follows the supply voltage increment by responding in the same ratio. In order to calculate the signal, the voltage as a result of the applied force is measured over the supply voltage according to

$$S = U_{measured} / U_{VCC} \ldots (7)$$

where, S is the signal and $U_{measured}$ and U_{VCC} are the measured and supplied voltages, respectively. According to this formula, the signal obtained at 10V of supplied voltage under 200mN of force (20g) is 30mV. This is a clear improvement by a factor of two, compared to the same signal obtained from the alumina-based millinewton sensor (250µm) under a force that is twice larger (table 2).

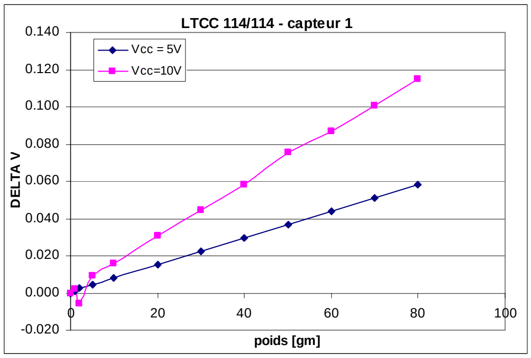

Figure 9. Response of the LTCC-based millinewton force sensor at two different supply voltages.

Table. 2. Comparison of sensitivities of millinewton sensors produced at LPM

	Alumina	LTCC
Force applied (mN)	400	200
Signal obtained (mV/V)	0.3/3	0.3/3

3. DISCUSSIONS

The obtained result has mostly been within implications of equation 6. Although an improvement of signal by approximately four times was expected by replacement of alumina by LTCC, it has only doubled. The major reason for this reduction is ascribed to the limited material incompatibility between the co-fired LTCC sheet and the screen-printed terminations. Different shrinkage behaviour of LTCC and the termination, which leads to deformation of the substrates, has recently been avoided by modifying the terminations chemically (figure 10). Such a modification matches the shrinkage behaviour of the materials and the deformation is reduced (figure 11).

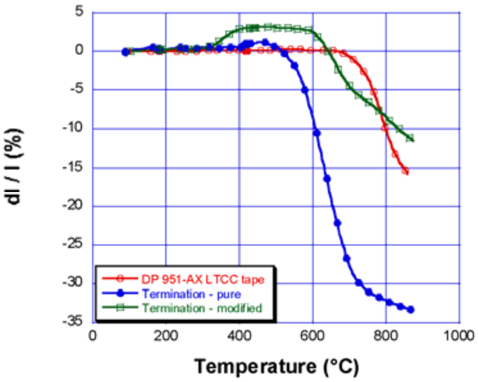

Figure 10. Dilatometry analysis of LTCC and the used termination (pure and modified).

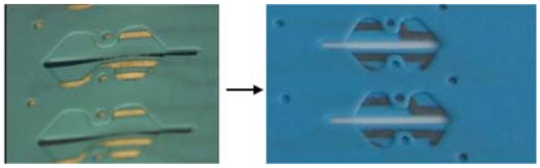

Figure 11. Modification of termination avoids deformation due to differential shrinkage.

4. CONCLUSIONS

Millinewton force sensor, which is originally based on the alumina substrate with integrated thick-film piezoresistor, has been modified by LTCC substrate. It has been shown that such a replacement increases the sensitivity of the sensor by two times in the first attempt, which is strongly expected to be further increased by improved material compatibility. Elastic modulus, fine sheet thicknesses and design flexibility offered by LTCC are addressed to be the major factors, which contribute to the obtained results.

5. REFERENCES

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