3D Force Sensor

Mariano Roberti[1*], Mário R. Gongora-Rubio[2] and Liliana Fraigi[1]
[1] National Institute of Industrial Technology (INTI), Argentina
[2] Institute for Technological Research of São Paulo State (IPT)
*Corresponding author: Mariano Roberti, Tel: (5411) 4724-6369, mariano@inti.gov.ar

Abstract

Force sensors are used in industry for weighing measurements. Basically it is an elastic element to which an appropriate type of strain sensor is bounded. The application of a force to the elastic element causes a deformation sensed by the strain sensor providing an electrical output proportional to the applied force. In the present work is proposed a novel structure designed for low cost compressive force sensing. Some features of this approach are: good performance to cost ratio, robust design, long-term stability and suitable for difficult environments. Fabrication methods of different meso-scale structures using Low Temperature Cofired Ceramics (LTCC) technology and preliminary sensor characterization are also presented.

Keywords: LTCC, micromechanical devices, piezoresistive sensors, force sensors.

Introduction

Micro-fabrication technologies have played an essential function in the development of MST. LTCC technology is a remarkable option for 3D sensors devices implementation with several advantages when compared with other micro-fabrication technologies [1-3]. Recently new LTCC- developments were introduced allowing new fabrication techniques for MST feasible [4, 5].

Embedded passive components (Micro-volume resistors) are well implemented in LTCC in order to improve MCM packaging density [4].

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In the present work is proposed a novel structure designed for low cost compressive force sensing. The structure consists of several green tape layers machined by using a printed circuit board prototyping CNC machine accompanied by metal electrodes and posts of thick film conductive and piezoresistive pastes, embedded in sacrificial materials.

Strain Sensors

The change in resistance of a resistor under applied stress is due to changes in the dimensions of the resistor and modifications of its conductivity as a result of micro-structural changes. The gage factor (GF) of a resistor is defined as the ratio of the relative change in resistance (ΔR/R) and the applied strain (Δl/l)

$$GF = (\Delta R/R) / (\Delta l/l) \qquad (1)$$

Metals are affected only by geometrical changes resulting in GF of 2 to 2.5. Semiconductors, thin film and thick film resistors displays higher gage factors. The longitudinal GF values of thick film 10K/□ resistors are usually between 9 and 20, as pointed out by [5], rendering an appropriate sensor for the proposed application.

Geometry of piezoresistive sensors implemented using thick film resistor materials are displayed in figure 1, (a) a planar structure, (b) a vertical structure, (c) a vertical structure with surrounded dielectric and in (d) the proposed novel post vertical structure suitable for z-axis force sensing. Resistance value for vertical structures is given by:

$$R = \rho \cdot \left(\frac{z}{x \cdot y}\right) \qquad (2)$$

With ρ = film resistivity; z= thickness of resistor and x and y lateral dimensions of resistor

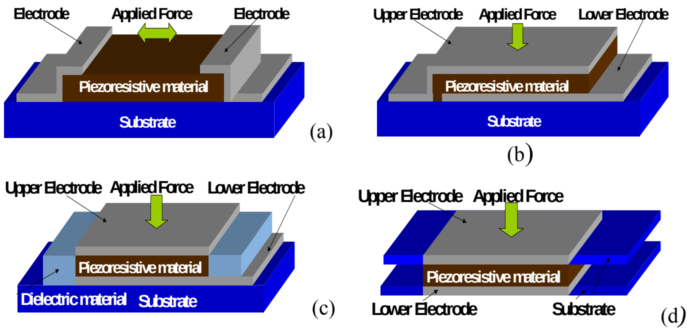


Fig. 1- Thick film strain sensor geometries.

Force sensors using thick film sensors have been proposed in [6,7], using planar geometry, see figure 1(a), but planar methods are generally indirect measurements. Z-axis sensitive devices exhibit higher GF, good thermal stability and are direct measurement technique when compared with conventional planar sensors, as observed in [8,9].

A design of z-axis piezoresistive force sensor, using geometry shown in figure 1b, was introduced in [10] obtaining high levels of strain.

Another implementation of a vertical z-axis thick-film piezoresistive resistor, surrounded with dielectric, for multipoint load sensor with sensing resistances of 2.5 KΩ and sensitivities of (ΔR/R) about 1.3% at 6 bar pressure was proposed in [11], using geometry depicted in figure 1c.

At this time we introduce a novel LTCC sensor conception for a z-axis piezoresistive sensor using geometry illustrated in figure 1d. Sensor is composed of a piezoresistive material post with upper and lower electrodes for electrical contact.

Sensor Design

Operation for compressive forces offer direct force measurement and allow the use of arrays for vectorial force decomposition, without mechanical translation.

In figure 2 is displayed the outline of a z-axis load cell force sensor.

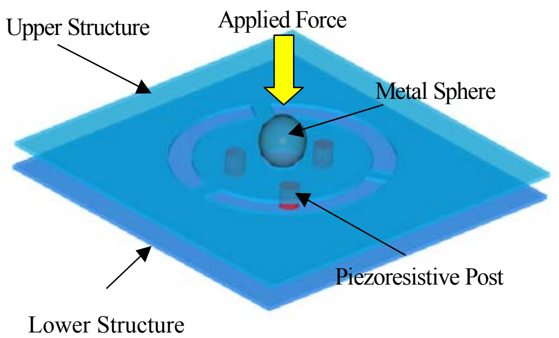


Fig. 2. 3D Force sensor outline.

Force is applied through a metal/ceramic sphere. Three posts at an angle of 120º to each other, connected to an upper structure, receive the decomposed force, each post sustain 1/3 of total applied force.

Strain (ε_z) in each one of the posts is given by:

$$\varepsilon_z = \frac{\Delta z}{z} = \frac{1}{E} \cdot \frac{4 \cdot F_z}{\pi \cdot d^2} \qquad (3)$$

With E = Young's module of piezoresistive material
F_z = Force in the z direction
d = Post diameter

The expected resistor variation of each post is given by:

$$\frac{\Delta R}{R} = GF \cdot \varepsilon_z = GF \cdot \frac{1}{E} \cdot \frac{4 \cdot F_z}{\pi \cdot d^2} \qquad (4)$$

The proposed sensor structure was simulated using COSMOS-designstar for static loads. In figure 3 can be seen sensor deformed shape superimposed to the non-deformed shape showing that applied forces are transferred to the sensor posts

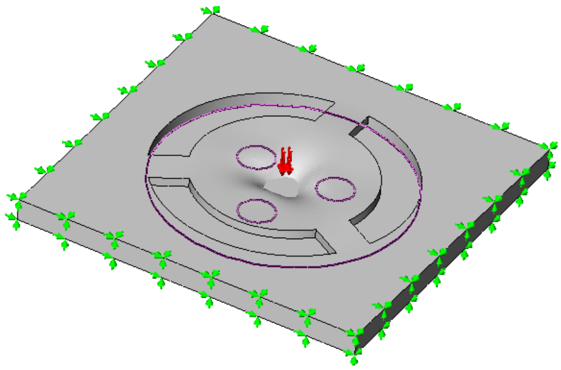


Fig. 3. 3D force sensor simulation results.

Materials

For sensor implementation we use Low Temperature Co-fired Ceramics materials to fabricate structural substrates for devices. Ceramic tapes provide an easy, inexpensive, and rapid platform for the integration of passives, electronics and microfluidics [1].

Mechanical properties of fired tape Dupont 951 system include a Young's modulus of 152 GPa, a Poisson's ratio of 0.17, and a material density of 3.1 g/cm^3.

The processing of the green ceramic tapes is usually done in three basic steps:

- ❖ Patterning of individual layers with via holes, resistors, conductors, dielectric pastes, depending on application;
- ❖ Collation and lamination of the tapes under pressure and temperature;
- ❖ Co-firing of the entire part to sinter the material.

LTCC composites are susceptible to plastic deformation upon lamination or under the stress of body forces once the glass transition temperature of the glass binder is reached during processing, hence sagging of a suspended cavity during lamination and sintering must be prevented.

Piezoresistive effects on thick film resistor materials are well investigated, providing evidence that thick film resistor can be used as strain gages. In this work we use available Dupont thick film

ISBN: 9974-0-0337-7

resistor pastes of QS family. For electrodes we use DuPont 951 compatible silver materials.

Recently a sacrificial volume technique for preserving an enclosed unfilled volume was introduced by Peterson et al. [2]. They used an insert of a sacrificial material that dissociates during the firing step and leaves no material residue after burnout.

Sacrificial material in solid form that uses a carbon tape [12] commercially available has been used in this work. We also modified the LTCC temperature sintering profile, changing the furnace atmosphere controlling the air/nitrogen ratio.

As introduced in [2] setter powder sheets and ceramic powder liners are uniform particle size ZrO_2 or Al_2O_3 materials with an organic binder contained in a paper-thin sheet, can eliminate sticking and reduces stresses on difficult to fire devices, we have used this materials for fabricating load cell sensors [12].

Force Sensor Fabrication

First implementation of the proposed device is presented in figure 4; it is formed of six LTCC layers (DuPont 951-AX). Three layers (L1- L3) were laminated with their corresponding electrodes facing up, one layer with a circular cavity (L4), for sacrificial materials, and finally two layers (L5-L6) laminated with electrodes downwards.

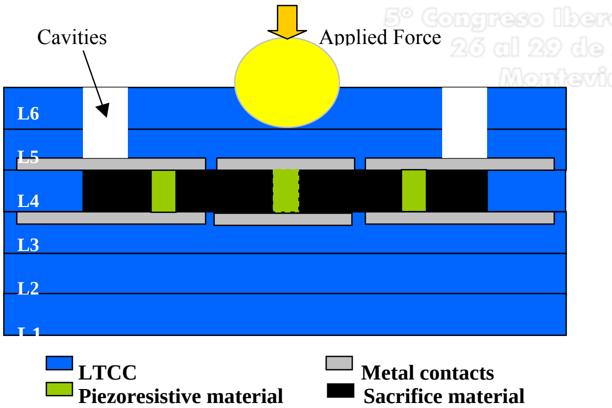
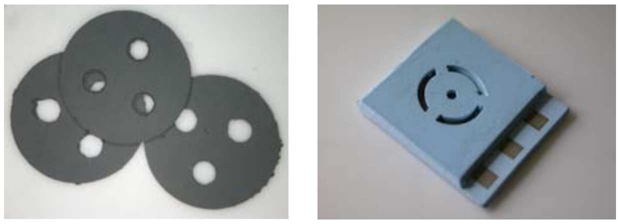


Fig.4. Internal electrodes sensor implementation

Inside the cavity a sacrificial material with three via holes is assembled. In via holes piezoresistive paste was poured. In order to avoid vias and simplify connections 1mm contacts we machined out the structure in layers (L3, L5). Several devices were made simultaneously, which reduced considerably fabrication times and cost. Green tapes were laminated at 100 ºC under pressure of 170 kgf/cm^2 during 10 min. Tapes were micromachined using a numerically controlled (CNC) milling machine, with tools of 250 µm, 500 µm and 1 mm in diameter. AUTOCAD software tool was used to design structures of each layer. In figure 5a is illustrated sacrificial tapes after machining and final assembled device, before sintering, see figure 5b. The device has dimensions of 11x11mm^2 including contacts. Electrodes were obtained by a silver paste (DuPont 6146) applied on the green tapes surfaces by means of screen printing, resulting in a total thickness of 50 µm.



(a) (b)

Fig. 5. (a) Carbon sacrificial tape and (b) final assembled device, before sintering.

In order to locate thick film piezoresistive post, a fugitive phase material, readily available was used. Cavity was filled with a high purity carbon black tape of 200µm thickness (TCS-CARB-1 from Harmonics, Inc.) used as sacrificial material with 3 holes of 1mm diameter. Some cavities in layers (L5, L6) were machined in order to ease gas flow (CO_2) produced during sintering.

Piezoresistances were obtained by pouring paste into via orifices. DuPont thick film commercial pastes of 1KΩ/□, 10KΩ/□ and 100KΩ/□ from the QS family were used. Finally, all the layers were stacked and laminated together at 100 ºC under pressure of 85 kgf/cm^2 during 20 min. After lamination, the device was sintered using modified LTCC temperature profile.

A second implementation of z-axis force sensor is presented in figure 6; it is formed of six LTCC layers (DuPont 951-AX). Three layers (L1- L3) were laminated with their corresponding electrodes in the lower face, one layer with a circular cavity (L4), for sacrificial materials, and finally two layers (L5-L6) laminated with electrodes in the upper face.

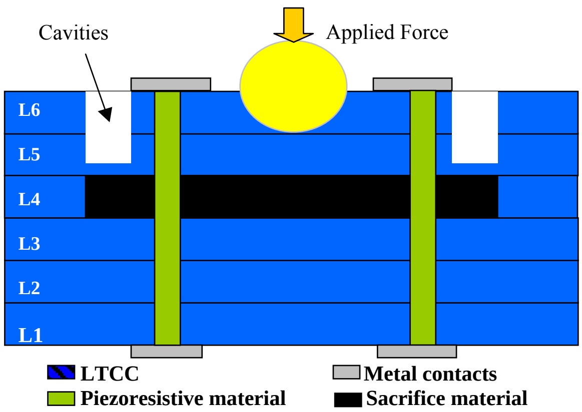


Fig 6. External electrodes sensor implementation

Inside the cavity a sacrificial material with three via holes is assembled. In these via holes piezoresistive paste was poured.

In order to locate thick film piezoresistive posts a Setter Powder SheetTM (SPS) or Ceramic Powder Liner TM (CPL) with thickness of 0.001 in from Harmonics, Inc. was used as sacrificial material. Remaining materials and processes are mostly the same as used in the latter sensor.

Figure 7 displays the fabricated device showing device posts, after removing upper sensor structure.

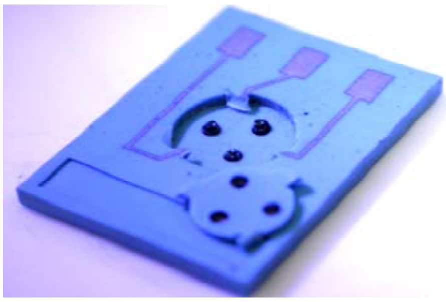


Fig 7. Fabricated external electrodes force sensor

Experimental Results

The characterization system for fabricated device is composed of a loading structure for applying static forces to the fabricated sensor, signal conditioning electronic circuitry, data acquisition and a PC workstation for data analysis, as shown in figure 8.

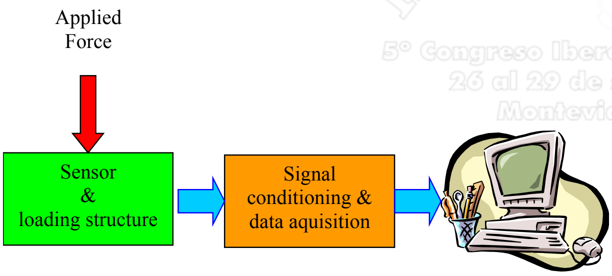


Fig 8. Instrumentation arrange for sensor characterization

Before we proceed with fabricated sensor calibration it was decided to test post behavior, so we implemented a single post device as shown in figure 9. Fabrication of test structure follows the same fabrication schedule mentioned in latter sections, rendering post of Ro = 1,3KΩ.

Temperature behavior of free posts (no mechanical loads) was accomplished obtaining good stability and having variations of no more than 1% of Ro.

Test structure was loaded from 0 to 15 N in a INSTRON force calibration equipment, displacement was monitored using a Laser displacement meter and resistance was measured using a Keithly 2000.

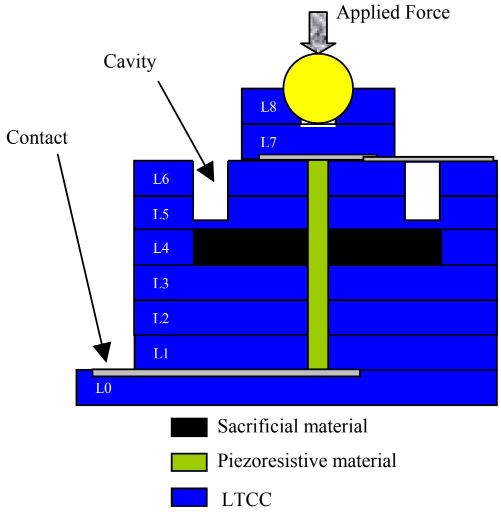


Fig 9.Post test structure

Loading results of 3D force sensor are presented in figure 10, at this time we measured %ΔR/R and ΔL.

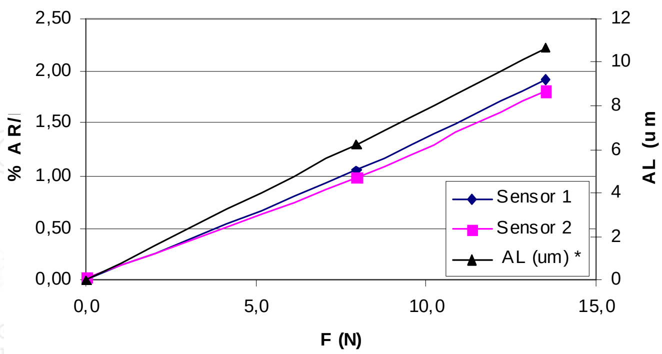


Fig 10. Post test structure loading results

Conclusions

LTCC technology allowed to produce z-axis compressive force sensor suitable for load cell applications.

Further measurements for sensor characterization in higher loads and temperature behavior are in progress.

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ISBN: 9974-0-0337-7

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