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Measurement of wireless pressure sensors fabricated in high temperature co-fired ceramic MEMS technology[*]

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Abstract: High temperature co-fired ceramics (HTCCs) have wide applications with stable mechanical properties, but they have not yet been used to fabricate sensors. By introducing the wireless telemetric sensor system and ceramic structure embedding a pressure-deformable cavity, the designed sensors made from HTCC materials (zirconia and 96% alumina) are fabricated, and their capacities for the pressure measurement are tested using a wireless interrogation method. Using the fabricated sensor, a study is conducted to measure the atmospheric pressure in a sealed vessel. The experimental sensitivity of the device is 2 Hz/Pa of zirconia and 1.08 Hz/Pa of alumina below 0.5 MPa with a readout distance of 2.5 cm. The described sensor technology can be applied for monitoring of atmospheric pressure to evaluate important component parameters in harsh environments.

Key words: High temperature co-fired ceramic (HTCC), Wireless, Micro-electro-mechanical systems (MEMS)
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1 Introduction

Requirements of instantaneous precise measurement continuously push the limit of dynamic testing technology. Until now, the testing technology referring to some important parameters under harsh environments has still been unreachable, especially those having wide applications in the area of equipment manufacture and micromanipulation, such as the large aircraft industry and high-efficient engine research (Cullinane and Strange, 1999; Pulliam *et al.*, 2002). In harsh environments, the degeneration of pressure-sensitive structures and electric interconnections lead to the failure of conventional sensors. The dynamic monitoring of the pressure in extreme environments is a vital problem at present, so fabricating a pressure sensor that can be widely used in harsh environments is extremely urgent (Fonseca, 2007). To meet the needs of industry, this paper initially employs high temperature co-fired ceramic (HTCC) micro-electro-mechanical systems (MEMS) technology to propose a prototype of the pressure sensors that can be created by a technical process with zirconia tapes and 96% alumina tapes respectively. In this paper, a passive wireless resonant telemetry scheme is adopted. Its operating principle is that the resonant frequency of sensors modulated by various pressures can be read by the external instrument. The general architecture of a telemetric measurement system is shown in Fig. 1.

A large number of wireless sensors for detection of different parameters have already been fabricated (Birdsell *et al.*, 2004; Birdsell and Allen, 2006; Chen *et al.*, 2008; Ong *et al.*, 2008). However, only a few low temperature co-fired ceramic (LTCC) pressure

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sensors are presently available. So the wireless pressure sensors fabricated from HTCC for use in harsh environments are demonstrated and measured. These sensors have the potential to be placed for use in harsh environments and make it possible to test pressure without the consideration of reliability. Moreover, this type of sensor exhibits many advantages over the piezoelectric counterparts, such as excellent stability and durability.

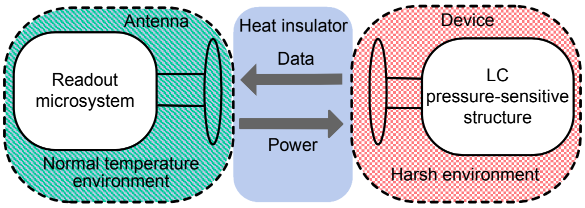


Fig. 1 General architecture of an inductive telemetric test system

2 Design

2.1 Principle of measurement

The magnetic link between two inductively coupled coils allows the impedance analyzer to measure impedance variation of the device wirelessly as the LC circuit of the device is excited. The test system and the test circuit principle are illustrated in Figs. 2 and 3, respectively. When the device is under pressure, the deformation of the membrane results in the change of the circuit capacitance, and thus the impedance of the device circuit also changes (Chen, 2008). By electromagnetic field coupling, the total impedance Z_0 tested from the antenna also changes and can be measured by an impedance analyzer (Fonseca *et al.*, 2002) (Fig. 2). The impedance Z_0 is given as

$$Z_0 = R_R + \mathrm{j}2\pi f L_R\left(1-\frac{f_R^2}{f^2}+\frac{k^2(f/f_0)^2}{1-(f/f_0)^2+(\mathrm{j}/Q)(f/f_0)^2}\right), \tag{1}$$

where f_R and f_0 are the self-resonant frequencies of the antenna electronics and device, respectively, $f_0=1/(2\pi\sqrt{L_sC_s})$, f is the sweeping frequency, k is the coupling coefficient, and Q is the quality factor of the device. In Fig. 3, M is the coefficient of mutual induction.

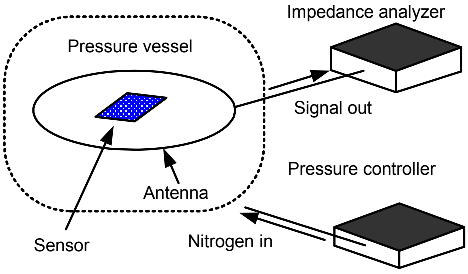


Fig. 2 Sensor test setup for measurement

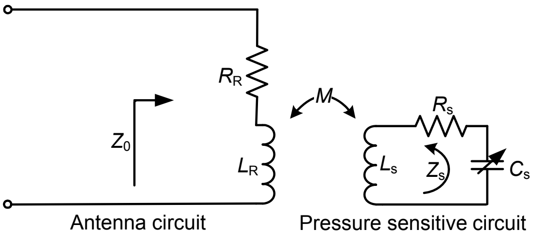


Fig. 3 Schematic of test system circuit

The device is excited at the resonance when $f=f_0$. The impedance phase magnitude reaches an extremum. If the impedance phase change is detectable during the frequency sweep, the self-resonant frequency of the device can be accurately characterized under different pressures. Further, the pressure is derived from the resonant frequency by a series of formulas elaborated in Fonseca (2007).

2.2 Device structure scheme

HTCC is a flexible ceramic green tape similar to LTCC which is produced by blending the ceramic powder, glass, and a specific amount of binder, and then employing the tape casting technology. Finally, the sheet is sintered at approximately 1500 °C. By heating, the glass component melts to bond the ceramic powder, which results in shrinkage of tapes (Table 1) and the tape becomes rigid after cooling. Some HTCC materials with excellent mechanic toughness property and thermo-stabilization can be used as pressure-deformable membranes. Through a lamination process and screen-printing (Imanaka, 2004), a desirable sensor embedding a pressure-deformable square cavity is fabricated. The sensor is composed of three layers: each electrode plate of a parallel-plate capacitor and a planar spiral inductor is connected in series on the top layer and the bottom layer, respectively; then both parts interconnect inside and form an LC resonant circuit finally (Fig. 4).

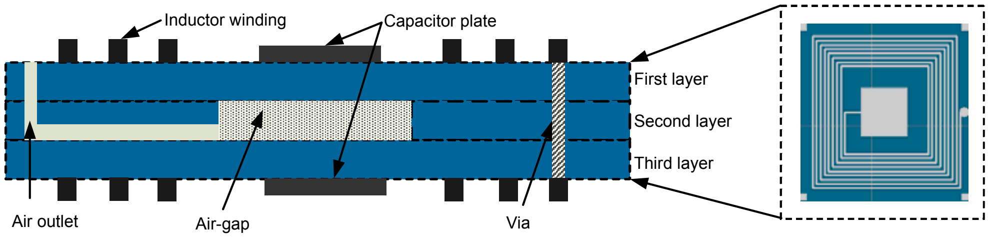


Fig. 4 Schematic cross section of the structure diagram for the designed sensor

Table 1 Characteristics of high temperature co-fired ceramics (HTCC) tapes

Tape	Green tape thickness (μm)	Fired shrinkage (%)	
		X/*Y*	*Z*
Zirconia	125	17.3±1.0	18.3±1.0
96% alumina	200	16.0–18.0	–

As shown in Fig. 5, when a uniform pressure p is applied, the pressure-deformable square membrane has a center deflection d_o. The membranes are clamped at the edge since they are made of the same material as the rest of the structure. The gap between the membranes with thickness t_m is t_g. For this case, the center deflection d_o is as given in Timoshenko (1984). By simulation using the ANSYS® software, the deflection, stress, and strain under 0.1 MPa are shown in Fig. 6.

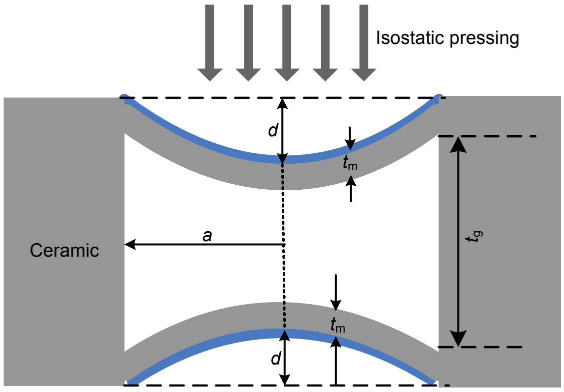
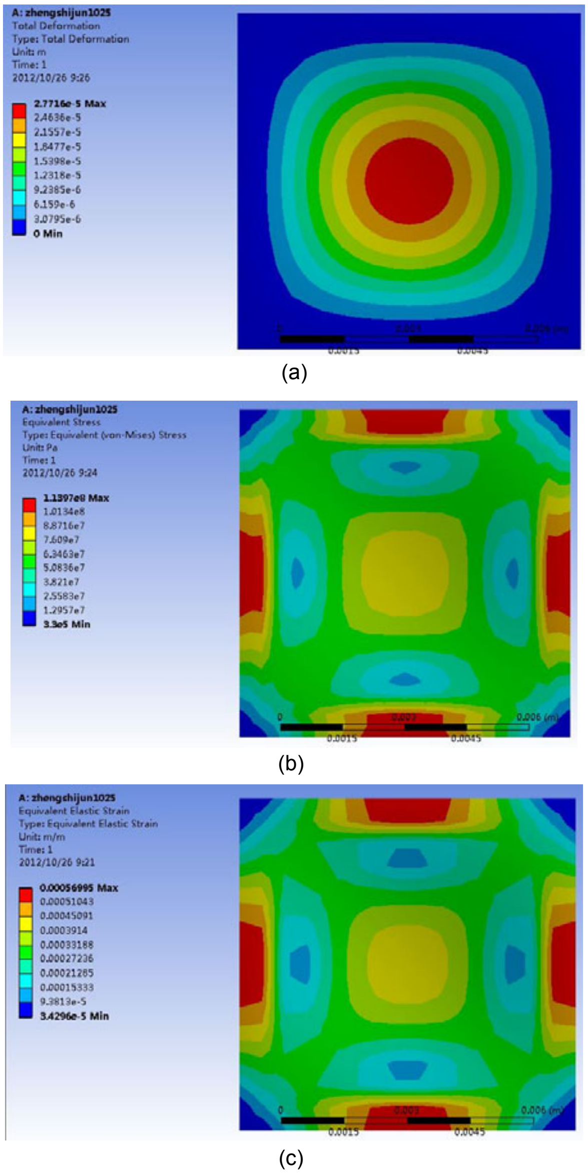


Fig. 5 Schematic cross section of a sealed cavity by two pressure deformable membranes

3 Fabrication

In the HTCC materials system, the green tape is generally used with high melting point metals such as Au, W, Mo for co-firing at 1500 °C, but the metals are



(a)

(b)

(c)

Fig. 6 Simulation of the uniformly loaded clamped square membrane on deflection (a), stress (b), and strain (c) load under 0.1 MPa

Young's modulus E=210 GPa, Poisson's ratio ν=0.32, t_m=100 μm, and membrane side length L=8 mm poorly conductive and must be sintered in a protective gas atmosphere. The common silver paste should be sintered in the air at 850 °C. Considering the fact that the tapes and paste need to be co-fired, a parallel fabrication processing is used and proves to be feasible. In this paper, we use porous platinum conductor paste to realize metallization and component formation (Wahlers *et al.*, 2012). The typical properties of platinum paste are shown in Table 2. Firstly, die-cutting is used to achieve an accurate cavity. Then, punch air outlet and via in the first and second layers and punch via in the third layer (Fig. 7). Three processed tapes are stacked in order according to the design requirements. The tapes and paste are co-fired at 1500 °C according to the firing curve shown in Fig. 8. A sacrificial layer (black part) used for providing a mechanical support in the cavity is illustrated in Fig. 7. The sacrificial layer is of importance for keeping the structure from collapse during lamination (Birol *et al.*, 2006; Malecha and Golonka, 2008). Without it, the cavity will be out of shape (Fig. 9).

Table 2 Typical properties of platinum paste

Parameter	Value
Resistivity* (mΩ/square)	30±10
Firing range (°C)	1500±10
Screen mesh (mesh)	325
Emulsion (μm)	25±5

* 12.5 μm fired thickness

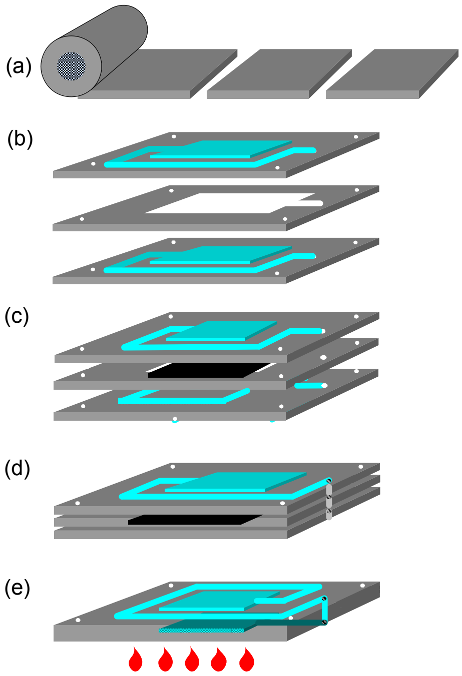


Fig. 7 Major fabrication steps
(a) Tape sheet cast; (b) Punching cavity and via; (c) Filling the sacrificial layer; (d) Lamination of layers; (e) Screen surface pattern and sinter

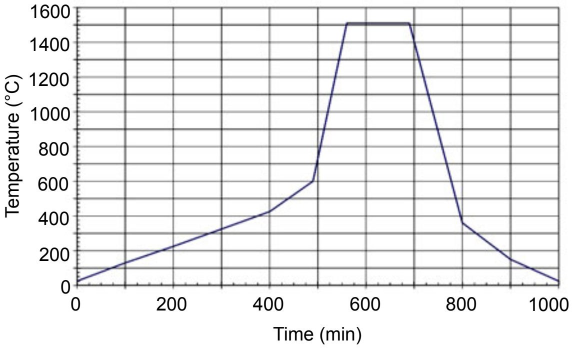


Fig. 8 Experimental firing curve

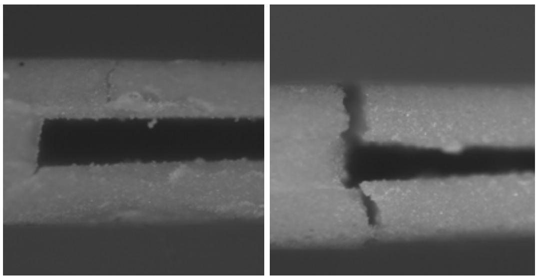
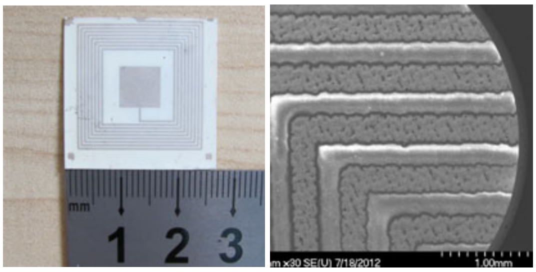

(a) (b)

Fig. 9 Comparison of the cavity of alumina after sintering: filling in a sacrificial layer (a) and nothing (b)

A set of parallel metal plates, acting as an integrated capacitor and surrounding spiral metal wires, acting as a planar inductor, are screen-printed on the tapes. When all processes are completed, the circuit wires of the device become conductive. The device is demonstrated in Fig. 10a and the dimension of the device is given in Table 3. A glass bead is used to seal the air outlet (Fig. 4). Put the 3M® glass bead on the outlet and then heat it at 850 °C for 30 min in the furnace, as shown in Fig. 11. After that the glass melts and fills the outlet (Fig. 12). When the sensor is cooling in the air, the air pressure in the cavity is about 0.1 MPa.

Table 3 Geometrical parameters of the device design

Tape	Membrane thickness (mm)	Cavity (mm×mm ×mm)	Device (mm×mm ×mm)
Zirconia	≈0.10	7×7×0.1	25×25×0.3
96% alumina	≈0.15		



(a) (b)

Fig. 10 Exposed circuitry ceramic pressure sensor with silver printed conductors (a) and SEM photo of square inductors (b)

Fig. 11 Furnace for air outlet sealing

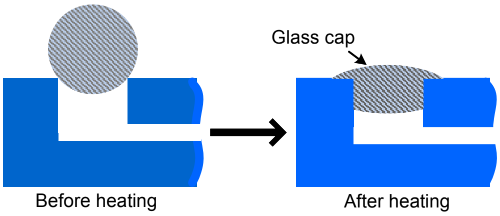


Fig. 12 Air outlet sealing process

4 Results and discussion

To complete the experiment, an Agilent® E4991 material analyzer is used to test the impedance of the device wirelessly. A set of experimental tests of the device has been carried out by varying the air pressure in the test vessel. The specific test results shown in Fig. 13 imply that the device possesses a capacity of good pressure response. The measured sensor characteristic is shown in Fig. 13. The frequency-pressure relationship is approximately linear, and the sensitivities of the zirconia sample and the 96% alumina sample are approximately 2 and 1.08 Hz/Pa at a readout distance of 2.5 cm, respectively. These results show that the device of zirconia material has better performance than the device of alumina material, which coincides with the fact that the toughness of zirconia is much better than that of alumina. Another possible reason is that the zirconia membrane is a little thinner than the alumina one. The sensitivity we found is better than that of the other LTCC sensors in Fonseca (2007) and Radosavljevic *et al.* (2009). The reason may be the use of the sacrificial layer; the air-gap can be made smaller, so the ratio of d/a in Fig. 5 is large. As a result, the variable capacitor is more sensitive to pressure. In the paper, the inductor windings of the sensor are square, so we can obtain more turns compared with round shape windings. The maximum test pressure limited by the pressure vessel is up to 0.45 MPa. In addition, the pressure sensitivity could be optimized by reducing the thickness of the membrane and enlarging the dimension of the cavity to improve the ratio of load-deflection or narrowing the gap between the upper and lower membranes by thinning the second layer of the sensor in Fig. 4. However, large cavity dimensions may cause the collapse of the membrane. After enduring 500 °C for 30 min in the furnace as shown in Fig. 14, the sensors keep good experimental performance as in the test environment of room temperature.

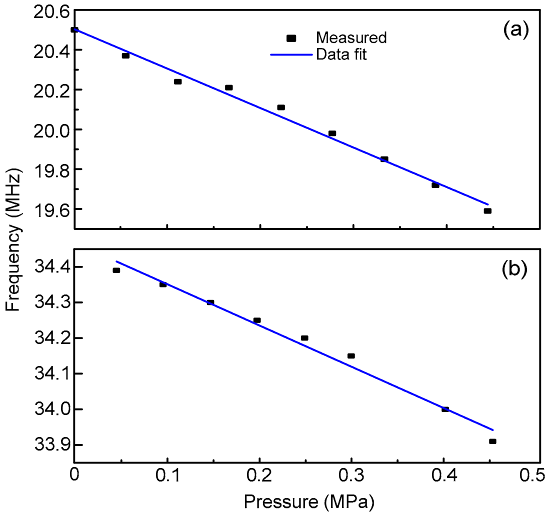


Fig. 13 Resonant frequency vs. pressure characteristic
(a) Zirconia sample; (b) 96% alumina sample

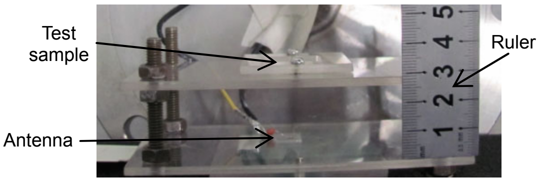


Fig. 14 Wireless sensor testing platform for interrogation distance

5 Conclusions and future work

In this work, wireless and passive pressure sensors of different HTCC materials, which have an advantage over existing sensors for non-contact measurement, are fabricated and the test is completed with experimental results. Here the distance between the device and antenna is about 2.5 cm. Otherwise, it is reasonable to improve the elastic performance of the pressure deformable membrane by reducing the thickness of capacitor plates, so the sensor sensitivity can be increased. Furthermore, the properties of the device operating in harsh environments need be confirmed under different pressures at high temperatures (>600 °C).

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