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Research Article

A Novel Interdigital Capacitor Pressure Sensor Based on LTCC Technology

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A novel passive wireless pressure sensor is proposed based on LTCC (low temperature cofired ceramic) technology. The sensor employs a passive LC circuit, which is composed of a variable interdigital capacitor and a constant inductor. The inductor and capacitor were fabricated by screen-printing. Pressure measurement is tested using a wireless mutual inductance coupling method. The experimental sensitivity of the sensor is about 273.95 kHz/bar below 2 bar. Experimental results show that the sensor can be read out wirelessly by external antenna at 600°C. The max readout distance is 3 cm at room temperature. The sensors described can be applied for monitoring of gas pressure in harsh environments, such as environment with high temperature and chemical corrosion.

1. Introduction

Passive wireless sensor has characteristics of having no batteries and contactless signal readout and nonpollution, which make it have extensive application prospects in many fields, such as high-temperature measurement, hermetic space, and rotating components. Wireless inductor sensor is a new type of wireless sensor. In recent years, LTCC is widely used in applications like RF circuits, microwave device, package, and so forth, but they seldom have been used to fabricate capacitive pressure sensors. LTCC technology is the method which can make multilayer ceramic tapes and printed conductive metal figures a whole multilayer interconnection structure by sintering at 800~950°C temperature. Passivewireless pressure measurement in harsh environments such as high temperatures has become increasingly critical in automotive, aerospace, and industrial applications [1–3]. Most pressure sensors are made by micromachining silicon, and they have many advantages in terms of small size and fast response. However, the circuitry ultimately limits the operational temperatures to <150°C [4–6]. Typical temperatures for high-temperature environments applications can range from 200 to 1000°C, requiring the development of novel sensor. The proposed sensor in this paper which is fabricated in LTCC green tapes based on LC resonant principle is prospective to solve those problems.

This paper proposes a passive wireless sensor for remote pressure monitoring in high-temperature environment and also can be used for environment with hazardous gas. It consists of a fixed inductor and variable capacitor. The noncontact measurement technology is used to obtain pressure information [7, 8]. The proposed pressure sensors are totally passive, which means that there are no batteries and the possibility for the occurrence of electric spark is eliminated, which is critical for the hazardous gas environment. The novel pressure sensor realized in LTCC technology can work at temperatures from 400 to 600°C. It is expected to wirelessly measure pressure up to 600°C and last up to 30 minutes.

2. Design

2.1. Principle of Measurement. The principle of measurement is based on a passive LC circuit. The sensor has two significant components, a planar spiral inductor and a variable interdigital capacitor which is a sensing element.

The resonant frequency of sensor can be retrieved from the well-known expression:

$$f_H = \frac{1}{2\pi\sqrt{L_S C_S}}. \tag{1}$$

L_s and C_s are inductance and capacitance of the sensor. It is evident that any variation of capacitance or inductance values results in a shift of resonant frequency f_H of the LC resonant circuit. The pressure sensor presented in this paper utilizes variation of external pressure to change capacitance values, which makes variation of sensor frequency. Therefore, the size of the external pressure can be got by the detection of resonant frequency change in the LC circuit.

Pressure measurement is tested using a wireless mutual inductance coupling method [9]. In order to obtain the frequency-pressure relationship, an Agilent E4991 impedance analyzer is used to test the sensors. The magnetic link between two inductively coupled coils allows the impedance analyzer to measure impedance variation of the device wirelessly as it is excited. The induction of antenna produces the alternating magnetic field. When the antenna is near the sensor, the magnetic energy is transmitted by the inductance coil of the LC circuit [10]. Antenna and sensor are contacted without wires. The power supply of sensor is electromagnetic wave energy. The antenna transmits energy to the sensor. It realizes the passive wireless detection. The wireless measurement way is presented in Figure 1.

The sensor resonant frequency can be obtained through testing antenna impedance phase with Agilent impedance analyzer. The total impedance of the reader antenna can be determined as

$$Z = R_a + j2\pi 2\pi_a \left[1 + \frac{k^2 (f/f_0)^2}{1 + j(1/Q)(f/f_0) - (f/f_0)^2} \right], \tag{2}$$

where R_a is the resistance of reader antenna, L_a is inductance of reader antenna, and Q is the quality factor of sensor. From (2), it is obvious that Z relates to the sensor resonant frequency f_0, and f_0 can be obtained by measuring input impedance Z.

k is the coupling coefficient between the sensor and the antenna and is given by

$$k = \frac{M}{\sqrt{L_s L_a}}. \tag{3}$$

M is the mutual inductance.

2.2. Sensor Structure Design. Figure 2 is a cross-sectional view of the interdigital capacitor sensor. Inductance is a plane spiral inductor. Capacitor is an interdigital capacitor.

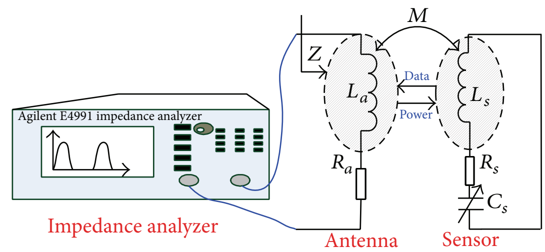

Figure 1: Schematic of test system circuit.

The sensor consists of four layers of LTCC ceramic tape. The first layer is sensitive pressure film of the sensor. Under external pressure, pressure sensitive membrane will produce deformation, causing the change of capacitance size and then the change of frequency. Inductor capacitor can be known from the following equation [11]:

$$L_s = \frac{\mu n^2 d_{\text{avg}}}{2} \left[\ln\left(\frac{2.46}{\rho_s}\right) + 0.2\rho_s^2 \right]. \tag{4}$$

In formula (4), μ is vacuum magnetic conductivity. It is a constant value. The spiral number of turns is n; the equivalent spiral representations have inner, outer, and average diameters d_{in}, d_{out}, and d_{avg}, respectively. $d_{\text{avg}} = d_1 + d_2 + \cdots + d_n/n$, $\rho_s = d_{\text{out}} - d_{\text{in}}/d_{\text{out}} + d_{\text{in}}$, ε_r is the relative dielectric constant of the LTCC green tape, and ε_0 is absolute dielectric constant in vacuum.

Interdigital capacitor can be known from the following equation [7]:

$$C_S = L_c (N_C - 1)\varepsilon_0 \frac{1 + \varepsilon_r K\left[\left(1 - \left(g_c/(w_c + g_c)\right)^2\right)^{1/2}\right]}{2K\left(g_c/(w_c + g_c)\right)}. \tag{5}$$

In formula (3), L_c is the length of the interdigital capacitor electrode. N_c is the number of the interdigital capacitor electrodes. g_c is the distance between one electrode and another in the interdigital capacitor. w_c is the width of the interdigital capacitor electrode. Based on the principle above, this paper designed a passive wireless pressure sensor in which the resonant frequency is about 40.68 MHz.

According to Figure 2, L_c increases with the increase in the external pressure. From formula (1) and formula (5), the frequency of the sensor decreases with the increase in the capacitance and also decreases with the increase in the external pressure.

3. Fabrication

LTCC is short for low temperature cofiring ceramic technology. The fabrication process is illustrated in Figure 2. The sensor consists of four layers of LTCC ceramic tape. The top ceramic tape creates the pressure sensitive diaphragm of the mechanical structure.

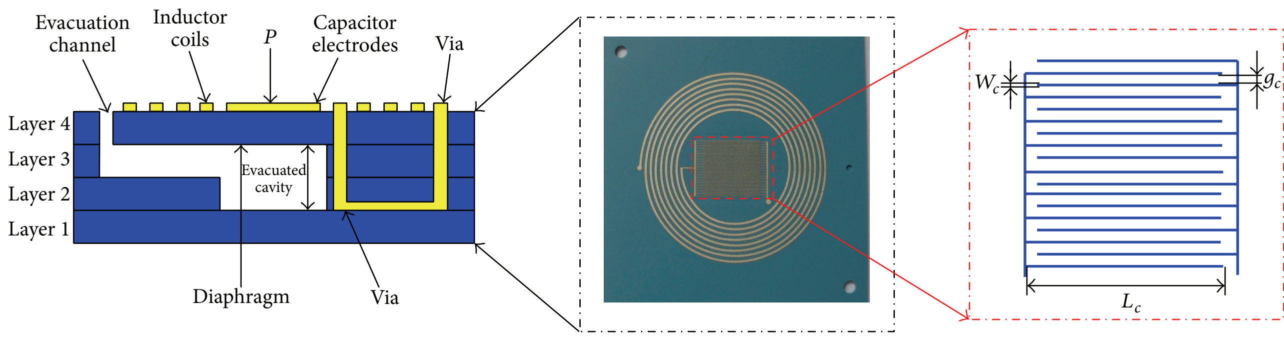

Figure 2: Schematic cross section.

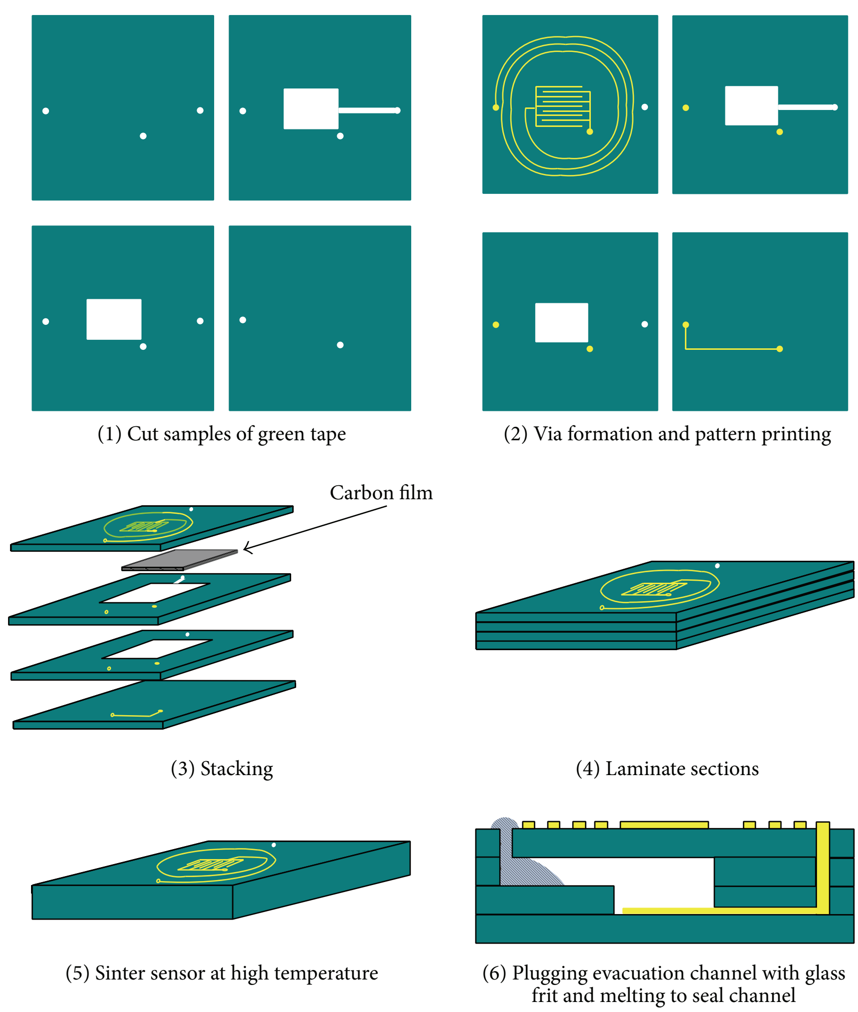

Figure 3: Fabrication process of passive wireless sensor.

The sensor main production process is shown in Figure 3 as follows.

(1) *Cut Samples of Green Tape*. The punching document is loaded on computer. Then put the LTCC green tape on the punching machine. Samples are cut by laser. Cavity structure and via will be formed, as shown in Figure 3, step 1.

(2) *Via Formation and Pattern Printing*. Inductor and capacitor were screen-printed, as illustrated in Figure 3, step 2. Via fill printing can ensure that the sensor circuit is connected.

(3) *Stacking*. In the lamination process, it is necessary to use carbon film to fill the capacitance cavity in order to avoid transmogrification in sintering. The stacking temperature is 40°C, as shown in Figure 3, step 3.

(4) *Lamination*. The lamination adopts isostatic pressing in water. Put the sensors sample into the laminating machine in the isostatic hydraulic pressure of 15 MPa for twenty minutes to make sensors have compact structure, as illustrated in Figure 3, step 4.

(5) *Slice*. After lamination, the sensors samples are to cut a square approximately 40 mm on a side prior to firing. This process can meet manufacture request.

(6) *Sintering*. The sensors samples are sintered in box furnace according to the set curve of temperature variation to harden the sample, as shown in Figure 3, step 5.

(7) *Seal*. In Figure 3, step 3, the carbon film is used to fill the cavity, which forms the evacuation channel. It is necessary to use the glass particles to fill the evacuation channel. This is done by placing ESL-4774-BCG glass frit (powdered glass) over the exit hole of the evacuation channel. The sample is placed in a vacuum tube furnace and heated at 540°C (4°C·min^{-1} ramp rate) and held for 10 minutes to melt the glass particles. The firing curve is shown in Figure 4. The powder average grain size is 20 μm, which is well suited for filling the evacuation channel, which can have a cross section of 800 × 800 μm. The sensors are dealt with for 10 minutes at 540°C to melt the glass particles, as illustrated in Figure 3, step 6.

Air-tightness measurement is performed to guarantee the validity of the sealing process, which can be judged by the existence of bubbles. The sensor is placed in the high-pressure environment and is inflated for 2 minutes, and then it is placed into the water. The exhaust hole is observed through a magnifying glass if any bubble appears. After that, sensor without bubbles into the water is placed into the pressure tank to test pressure response. Theoretically, the frequency will decrease as the external pressure increases. In testing progress, the external pressure is 1 bar and is kept for at least 5 min and the frequency is recorded. If frequency is constant, it indicates that sensor has considerable air tightness.

4. Experiments

4.1. Pressure Measurement. The curves of magnitude and phase in the antenna port are shown in Figure 5. From Figure 5, it can be seen that the antenna and the sensor are coupled well. The frequency-pressure relationship of the sensor is shown in Figure 6. The frequency of the sensor decreases with the increase of the external pressure. The frequency-pressure characteristics present approximately linear, and the sensitivities of the interdigital capacitor pressure

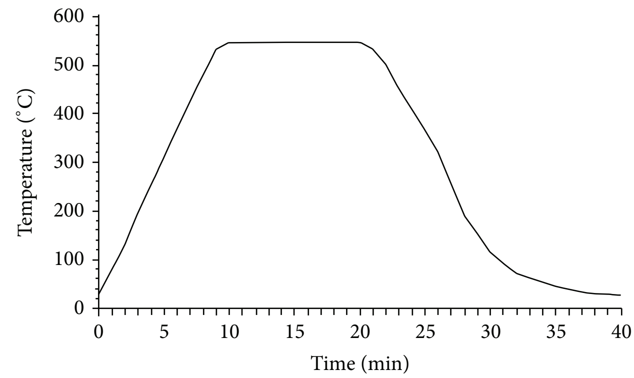

Figure 4: ESL-4774-BCG firing profile.

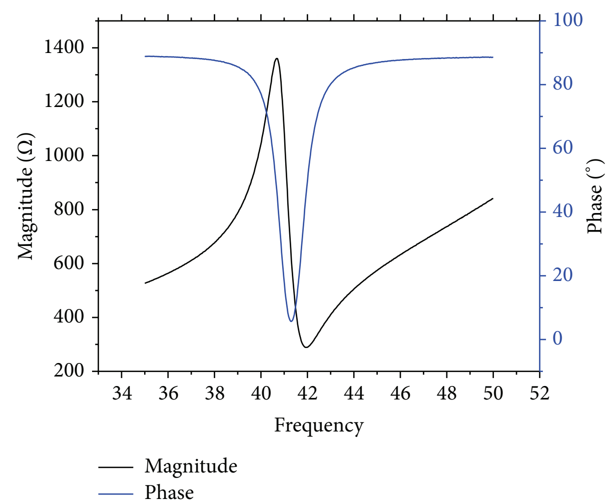

Figure 5: Measured magnitude and phase versus frequency for the pressure sensor.

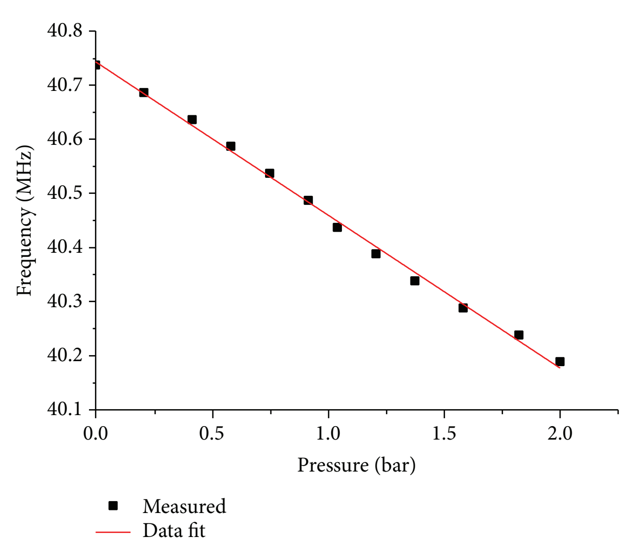

Figure 6: Resonant frequency versus pressure relationship.

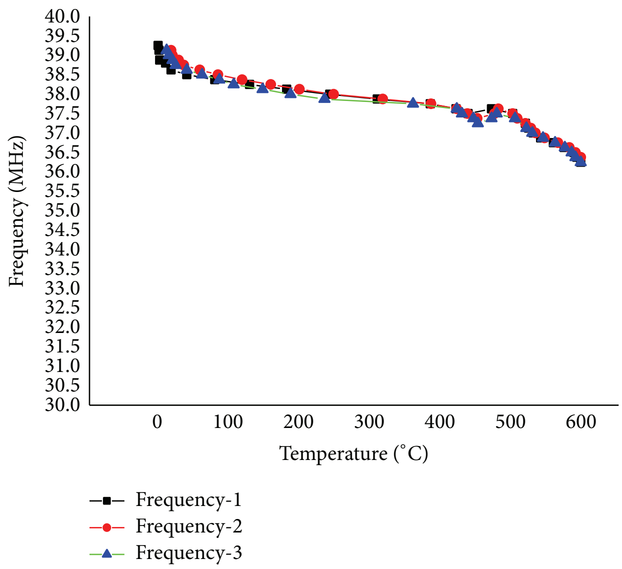

Figure 7: Resonant frequency versus temperature relationship.

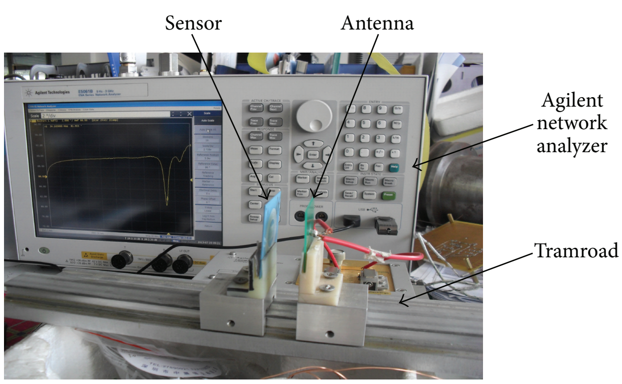

Figure 8: Photo of test system circuit.

sensor are approximately 273.95 kHz/bar with a readout distance of 25 mm. In the paper, the inductor windings of the sensor are circular; the quality factor Q of circular inductor is better than square inductor. The maximum test pressure limited by the equipment is 2 bar. Otherwise, the pressure sensitivity could be optimized by enlarging the dimension of the evacuated cavity to improve the ratio of load-deflection.

4.2. Temperature Measurement. In order to verify the high-temperature performance of sensor, a high-temperature experiment is required. We use tungsten filament as the test antenna. The test temperature is 25–600°C. Heating process is as follows: we measured the sensor from room temperature to 600°C and then at 600°C for 30 min. The frequency-pressure relationship of the sensor at room temperature is shown in Figure 7.

These results show that the resonant frequency of sensor decreases with the increase of temperature, which coincides with the fact that the relative dielectric constant ε_r of the LTCC green tape is changing with temperature. Finally, the heat stability test is carried out. Sensors left at 600°C over a 12 h period did not exhibit a change in resonant frequency or pressure sensitivity nor did they exhibit hysteresis.

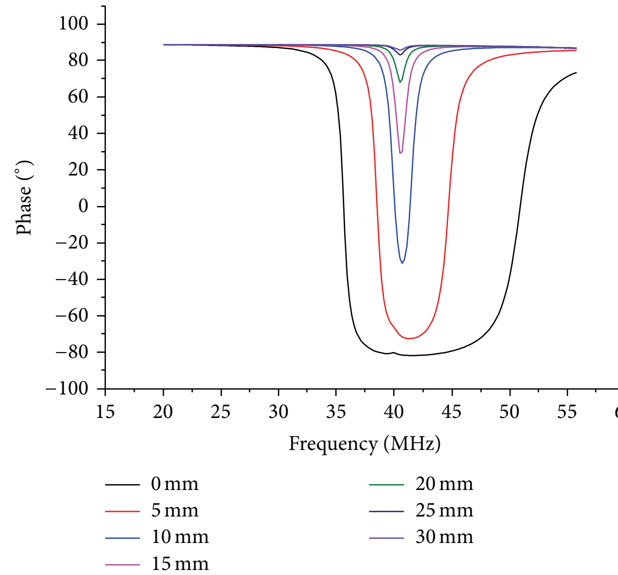

Figure 9: Coupling distance measurement.

4.3. Readout Distance Measurement. In order to test the coupling performance of the sensor, we set up as shown in Figure 8 test platform. The sensor and the antenna are placed in parallel. Figure 9 shows the coupling relationship between distance and phase.

The distance between sensor and antenna is 0 mm; the peak of the phase is flat. The distance between sensor and antenna is 10~20 mm; the phase has a very sharp peak. The distance between sensor and antenna is 30 mm; coupling waveform is less obvious. The distance between sensor and antenna is far-forth than 30 mm; sensor can no longer be coupled with the antenna.

5. Conclusions

In this paper, a passive contactless pressure sensor was fabricated using LTCC technology. The sensor detected pressure variations by using changes in its resonant frequency. The test results show that the resonant frequency of sensor decreased with the increasing of external pressure. The sensitivity of the resonant frequency change is 273.95 KHz/bar. Experimental results showed that the data of external pressure can be detected at 600°C with a distance of 25 mm and also that the sensor has higher stability at this temperature. Furthermore, the proposed sensors can be used to measure pressure at high temperature (400–600°C).

Conflict of Interests

The authors declare no conflict of interests.

Acknowledgments

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