WIRELESS MICROMACHINED CERAMIC PRESSURE SENSORS

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ABSTRACT

In high temperature applications, such as pressure sensing in turbine engines and compressors, high-temperature materials and data retrieval methods are required. The microelectronics packaging infrastructure provides well-developed, high temperature ceramic materials, processing tools, and processing techniques that have the potential for applicability in high temperature sensors. A completely passive wireless telemetry scheme, which relies on a frequency shift output, has been integrated with the sensors, thereby eliminating the need for contacts, active elements, or power supplies to be contained within the sensor. This simplicity of sensor design allows the sensor to be exposed to elevated temperatures. As a proof-of-concept, a wireless micromachined ceramic pressure sensor has been designed, fabricated, tested, and, compared with theoretical models. Sensors have been operated up to 200 °C and in pressure ranges from 0-1 bar and from 0-100 bar. The measured sensitivity of a fabricated sensor, expressed in frequency shift per pressure difference, is 2.6 MHz/bar, which compares well to the theoretically determined sensitivity of 2.2 MHz/bar.

INTRODUCTION

Micromachined silicon pressure sensors are widely utilized in industry. In general, the pressure sensor design is based on a flexible silicon membrane as the sensing element, coupled with silicon piezoresistors or a capacitive structure and silicon circuitry for data retrieval. These sensors are well developed and have been documented extensively in the literature [1]. However, micromachined silicon sensors are subject to temperature limitations due to piezoresistor temperature sensitivity and the relatively poor mechanical properties of silicon at higher temperatures. Thus, applications such as sensing pressure in turbine engine compressors require other sensors that offer high temperature stability.

In the literature, potential high-temperature materials have been investigated as an alternative to silicon. Silicon carbide, polycrystalline diamond and ceramic materials have been reported as high-temperature materials for sensor fabrication [2-3]. Silicon carbide pressure sensors employ the flexible membrane design and use piezoresistors to measure pressure changes. The incorporation of silicon carbide circuitry is also possible in order to retrieve the pressure data. Polycrystalline diamond pressure sensors also employ a flexible membrane and piezoresistors. These technologies show great promise for integrated high temperature pressure sensors, but their manufacturing infrastructure is not nearly as well developed as that for silicon and electronic packages for silicon.

The microelectronics packaging industry offers a well-developed ceramic packaging procedure using ceramic co-fireable tape. The ceramic tape consists of alumina particles and glass particles suspended in an organic binder, which is subsequently fired to form a ceramic structure. In general, this type of tape is referred to as low temperature co-fireable ceramic (LTCC) as the typical curing (firing) temperature is 900°C [4]. Ceramic tapes made solely from alumina particles are also available and have curing temperatures above 1600°C. These high temperature characteristics indicate that the ceramic tape may be an excellent choice for the fabrication of pressure sensors for high temperatures.

BACKGROUND

The microelectronics packaging infrastructure has developed ceramic multi-layer multi-chip modules as a means of complex packaging. A simple diagram of this procedure is given in Figure 1. The layers of ceramic tape are punched to form vias and are metallized to form conductor lines. The layers are then aligned and laminated together in a hot press. The package is fired in a furnace to bake off the organics and form the final package. Circuit chips are then soldered to the metal pads of the package. The co-fired ceramic tape can also be used to fabricate a pressure sensor. A slight modification of standard package fabrication techniques allows the creation of a thin flexible membrane that can sense pressure. In addition, ceramic packaging technology allows for the embedding of integrated passive elements (resistors, inductors, and capacitors) in the body of the package itself, which can be used for passive wireless communication.

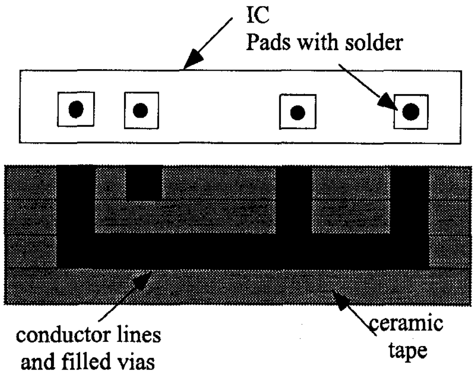

Figure 1. Simplified schematic of multilayer tape-based ceramic package.

Conventional micromachined pressure sensors depend on some type of interface with the sensing element (e.g., flexible diaphragm, piezoresistors, and capacitive elements) to read out the pressure data. Recognizing that at extremely high operating temperatures, simplicity of the sensor is desirable, a completely passive, wireless telemetry system that requires no physical contact with the sensor and no active elements such as power supplies, transistors, or batteries, is employed.

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A schematic of the wireless pressure sensor concept is shown in Figure 2. The sensor consists of a sealed cavity, ideally containing vacuum, on which two capacitor plates are formed. If either the top or the bottom (or both) bounding sides of the cavity are made of a flexible ceramic diaphragm, the value of this capacitor will change with pressure. In order to measure this capacitance change, a resonant technique is employed, in which a planar spiral inductor coil fabricated using ceramic-based integral passives techniques is electrically connected to the capacitor. These components form a passive resonant LC circuit, where the resonant frequency is given by [5]:

$$f_o = \frac{1}{2\pi\sqrt{L \bullet C(P)}} \qquad (1)$$

Thus, as the external pressure increases, the capacitance increases and the resonant frequency of the LC circuit will decrease.

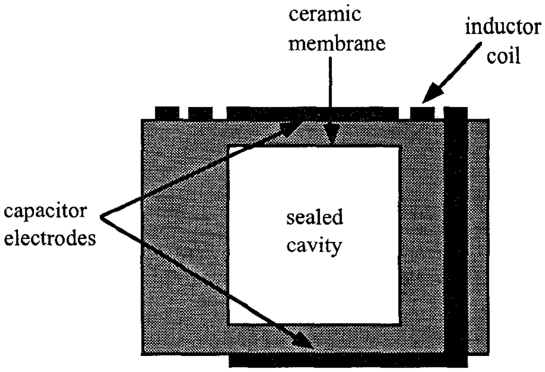

Figure 2. Pressure sensor concept.

To achieve passive wireless telemetry, the circuit is placed in proximity to an external loop antenna coil and the impedance and phase response of the antenna coil are monitored as a function of frequency. At frequencies far from the sensor frequency (and below the self-resonant frequency of the antenna itself), the antenna appears as an inductance, with a rising impedance response with frequency and a phase shift of +90 degrees. At the sensor resonant frequency, the antenna impedance decreases and the phase response of the antenna drops from +90 degrees. Although the magnitude of the phase peak depends upon the details of the specific sensor-to-antenna coupling, the position (i.e., frequency) of the peak does not. Thus, this wireless data retrieval scheme should also work for a sensor in motion within the antenna (e.g. mounted on a moving part). In addition, it is possible to have an array of such sensors, with each sensor designed to have a distinct 'center' frequency (i.e., frequency given by equation (1) under zero applied pressure), with the number of such sensors limited by the available frequency bandwidth.

DESIGN AND FABRICATION

The design of the sensor involves the creation of the flexible membrane, the sealed cavity, and the integration of the LC resonant circuit. The basic structure and assembly is shown in Figure 4. To create the flexible membrane, sealed cavity, and ultimately the capacitor, a three-layer structure is used. The first layer, which becomes the flexible membrane, consists of one sheet of ceramic tape (Figure 4(a)). The second layer consists of at least one sheet of ceramic tape with a hole punched into it. Finally, the third layer consists of at least one sheet of ceramic tape. By increasing the number of sheets of ceramic tape in the third layer, the layer becomes less flexible and less sensitive to pressure. The layers are aligned and laminated together in a hot vacuum press and fired in a furnace (Figure 4(b)). The final structure is shown in Figures 4(c) and 4(d).

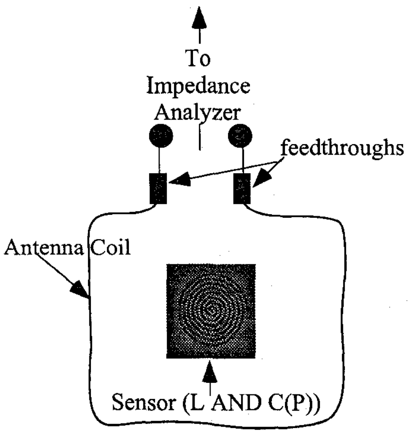

Figure 3. Wireless passive telemetry for pressure sensing.

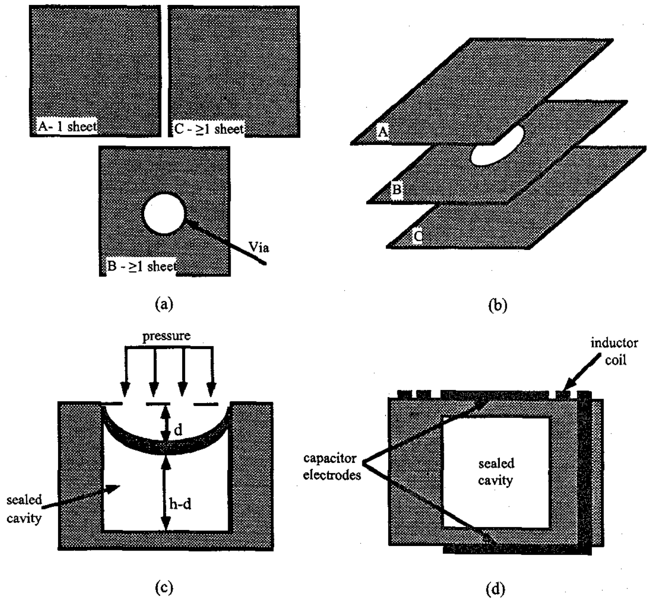

Figure 4. Diagram of basic concept structure. (a) 3 layers of ceramic tape, (b) assembly and lamination of 3 layers, (c) final package. (d) sensor design concept

The sensor is fabricated using 4 sheets of Dupont 951AT ceramic tape [4]. The tape consists of alumina and glass particles suspended in an organic binder. Each sheet is cut to a size of 2.5 inch square with a thickness of ~100µm. Of the four sheets, two are punched to create the via for the sealed cavity. The diameter of the via is 7.6mm. The four layers are aligned in a press mold that consists of two aluminum plates that are 2.5 inches square and 0.25 inches thick. The ceramic sheets are laminated together in a hot vacuum press for 10 minutes at a press temperature of 70°C and a press force of 9.38 tons under ambient vacuum. After lamination, the sample is cut down to a 1.5 inch square before firing. The sample is fired in a box furnace in air for 30 minutes at 500°C to bake off the organics and then for 20 minutes at 850°C to melt the glass particles and harden the sample.

To create the LC circuit, the top side of the sensor is DC sputtered with an electroplating seed layer of 500Å of titanium followed by 3600Å of copper. Shipley 5740 photoresist is used to create a plating mold that will define the inductor coil and one electrode of the parallel plate capacitor. Using a standard copper electroplating bath, copper is electroplated through the photoresist molds to a thickness of ~28μm and the plating mold and seed layer are removed using wet etching. On the back side of the sensor, the other electrode of the capacitor is formed using a DC sputtered titanium/copper layer sputtered through a shadow mask. Contact from the outer arm of the inductor coil on the top side of the sensor to the capacitor electrode on the back side is made using Dupont 6160 silver-filled external conductor paste for co-fireable tapes. A diagram of the fabrication process is given in Figure 5. A picture of the fabricated sensor is given in Figure 6.

SENSOR OPERATION

A diagram of the wireless ceramic pressure sensor test setup is shown in Figure 7. The sensor is placed in a chamber in which both the ambient pressure and the ambient temperature can be varied. An antenna coil is placed in the chamber in proximity to the sensor and connected to an HP4194A impedance analyzer by means of feedthroughs from the chamber. The impedance analyzer records the impedance and phase of the antenna coil while sweeping over a frequency range that includes the center frequency of the sensor. The phase of the inductive loop antenna is +90° except at the resonant frequency of the sensor. At the resonant frequency, the sensor couples to the antenna coil and causes a dip in the phase from +90°. As the chamber pressure increases, the ceramic membrane will deflect causing an increase in the sensor capacitance and a decrease in the resonant frequency and thus, the phase minimum will shift downward in frequency.

Wireless pressure and temperature tests were performed using an HP4194A impedance analyzer, a Parr 4570 pressure vessel for high pressure tests, and a VWR vacuum oven for low pressure as well as temperature tests. Figure 8 shows the raw data obtained, phase versus frequency, for zero and full-scale (1 bar) applied pressure for a single sensor. In Figure 9, the frequencies corresponding to the phase minima of Figure 8 are shown for a variety of pressures between zero and 1 bar, and at two temperatures, 25°C and 200°C. Figure 10 shows the high pressure (0-100 bar) response of the sensor.

For the results in Figures 8 and 9, the pressure sensor was designed to have a post-firing electrode radius of 5mm, a membrane thickness of 96μm, and a membrane-to-membrane gap spacing of 161μm. The sensitivity of the sensor was calculated from the measured data to be 2.6MHz/bar. The same sensor was tested at 25°C and 200°C and except at low pressures, little difference is seen in sensor performance at the two temperatures.

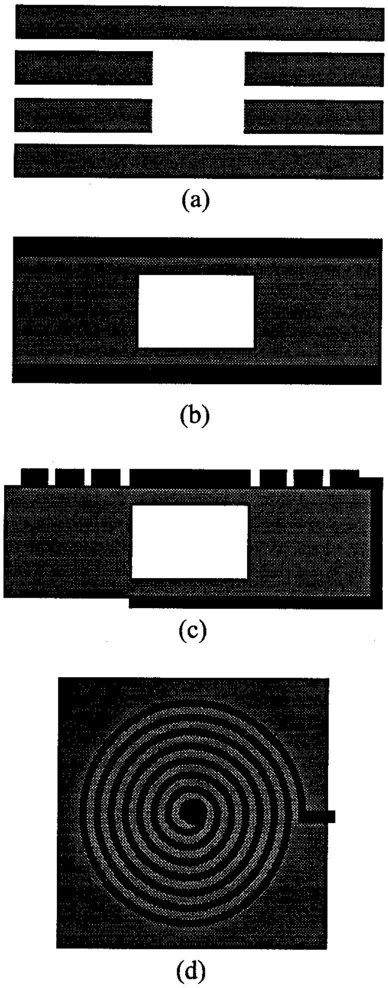

Figure 5. Ceramic micromachined pressure sensor fabrication. (a) ceramic tape layers punched and aligned. (b) after lamination, firing and metallization. (c) after electroplating coil and electrodes. (d) top view of wireless ceramic pressure sensor.

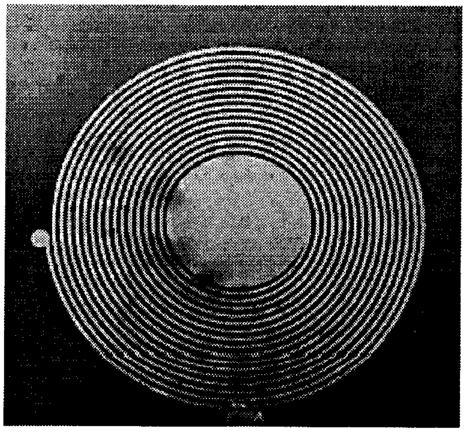

Figure 6. Photomicrograph of a typical micromachined ceramic pressure sensor.

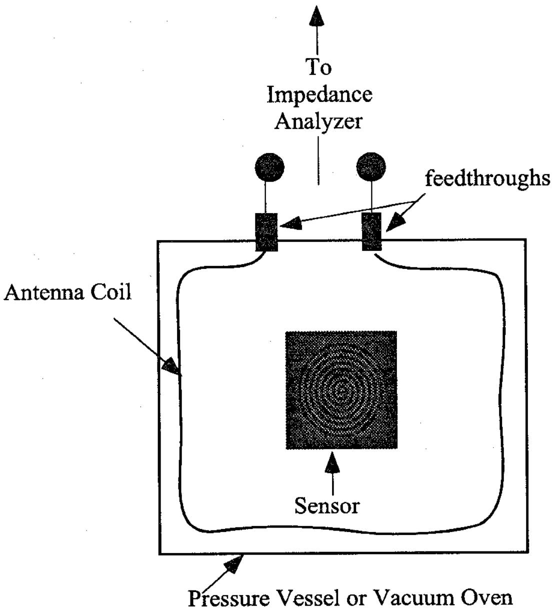

Figure 7. Diagram of pressure and temperature test setup.

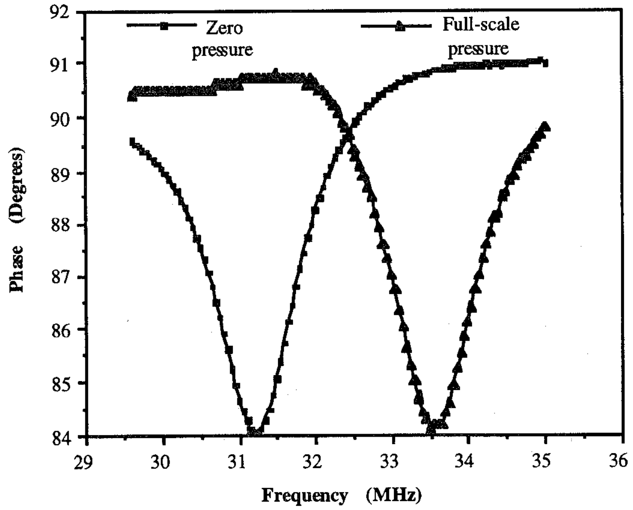

Figure 8. Phase versus frequency for zero and full scale applied pressure (0-1bar).

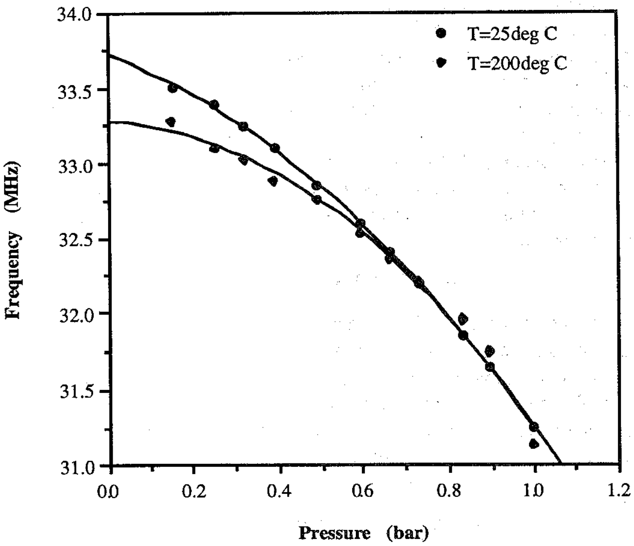

Figure 9. Frequency versus pressure for 25°C and 200°C (0-1bar)

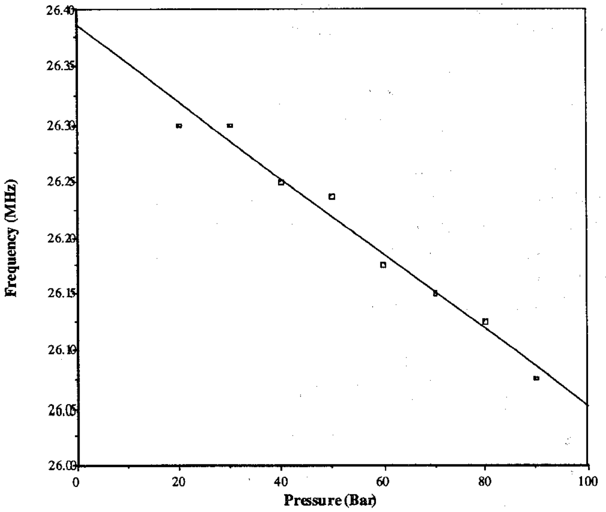

Figure 10. Frequency versus pressure for high pressure (0-100bar)

Sensors were also measured at high pressures (0-100 bar) and room temperature, and the results are shown in Figure 10. This pressure sensor was designed to have a post-firing electrode radius of 3.8mm, a membrane thickness of 96μm, and a membrane-to-membrane gap spacing of 161μm. The sensitivity for this sensor as calculated from the measured data is S=6.4kHz/bar. One possible explanation for this reduced sensitivity is that the sensor is operating in touch mode at these pressures. Theoretical modeling (described below) indicates that this is a likely explanation. This phenomenon can be avoided if desired by making the membrane radius smaller and/or by making the electrode gap larger.

SENSOR MODELING

Theoretical models for deflection of circular diaphragms and the associated capacitance were used to model and predict the behavior of the sensor. It is assumed, for this analysis, that only one membrane of the sensor deflects. For a clamped circular plate under zero residual stress that is subjected to both stretching and bending, the deflection is given by [6]:

$$d_o = \frac{Pa^4}{64D}\cdot\frac{1}{1+.488\left(d_o/t\right)^2}, \qquad (2)$$

where d_o is the deflection of the plate, a is the radius of the plate, t is the thickness of the plate, P is the applied pressure, and D is the flexural rigidity of the plate and is given by:

$$D = \frac{Et^3}{12(1-\upsilon^2)}, \qquad (3)$$

where E is the Young's modulus, and ν is Poisson's ratio. Using this equation, the amount of deflection for a given applied pressure is predicted. To determine the change in capacitance as a function of the deflection, a model given by [7]:

$$\frac{C_s}{C_o} = \sum_{i=0}^{\infty}\frac{1}{2i+1}\left(\frac{d_o}{h}\right)^i \qquad (4)$$

was used. In this equation, do is the deflection as determined from the deflection equation *(2)* and h is the electrode gap. This equation assumes that only one electrode is deflecting over a rigid ground electrode. The resonant frequency was then determined from equation *(1)* expressed in terms of the undeflected capacitance and resultant frequency f_o:

$$f = \frac{f_o}{\sqrt{C_s/C_o}}, \qquad (5)$$

where f_o is the measured resonant frequency at zero applied pressure, and $\sqrt{C_s/C_o}$ is determined from equation *(4)*. The measured resonant frequency is used instead of the calculated resonant frequency because the calculated resonant frequency does not allow for the parasitic capacitances associated with the windings of the inductor coil and the conductive paste that connects the inductor to the capacitor.

A plot of the predicted behavior of resonant frequency versus pressure over the pressure range 0-1 bar, as calculated from equation *(5)* and as measured by the sensor shown in Figures 8 and 9, is given in Figure 11. The sensitivity of the pressure sensor as determined by the model was 2.2 MHz/bar. Although the calculated sensitivity and the measured sensitivity are similar, there appears to be a difference in functional form between the model and the data. There are a number of reasons for this discrepancy, including the possibility that the lower capacitor electrode is also deforming in response to the applied pressure. Since the lower and upper ceramic membranes are the same thickness, and the only additional stiffening effect on the lower membrane is due to the electroplated copper lower electrode (as opposed to the sputtered upper electrode), such lower electrode deflection is likely to occur. In spite of this model limitation, agreement between the predicted and measured sensitivities is good.

The model has also been used to explain the behavior of the sensors over the high pressure measurement range (up to 100 bar), as shown in Figure 10. Over these pressure ranges, the model predicts that the two ceramic membranes are touching. This prediction can explain the reduced sensitivity of the sensor in these pressure ranges as observed in Figure 10.

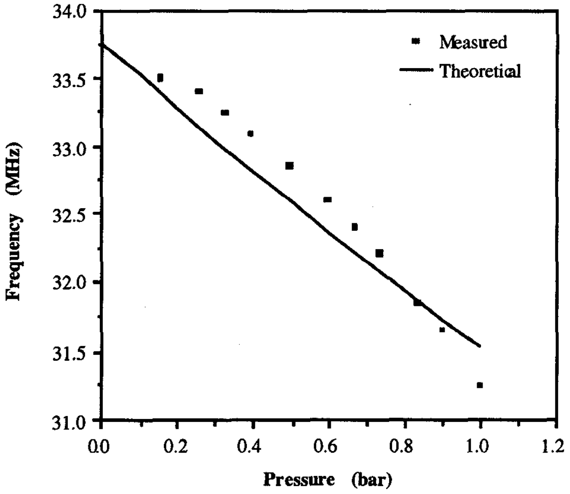

Figure 11. Comparison of theoretical to actual pressure data.

SENSOR ARRAY INVESTIGATION

The wireless telemetry scheme can be expanded to include measurement of a number of sensors, each with its own center frequency, limited only by bandwidth. For example, by keeping the capacitor size constant (so each sensor has nominally similar pressure response), and sizing the inductor associated with each sensor in such a manner that each sensor has a distinct undeflected center frequency as given by equation *(1)*, a number of sensors can be read out with a single antenna. Alternatively, a number of sensors with different capacitors (and therefore different mechanical responses) can be read out, thus extending the dynamic range of the sensor system.

An experiment to verify this readout technique was carried out. Three sensors with different center frequencies were tested simultaneously using the same antenna coil. The results of this experiment are shown in Figure 12. Three distinct peaks, corresponding to the three sensors, are evident. The variation in peak height for the three sensors reflects different degrees of sensor/antenna coupling (i.e. proximity of the sensor to the antenna coil). However, since to determine pressure only the peak position is required, this difference in peak height is acceptable.

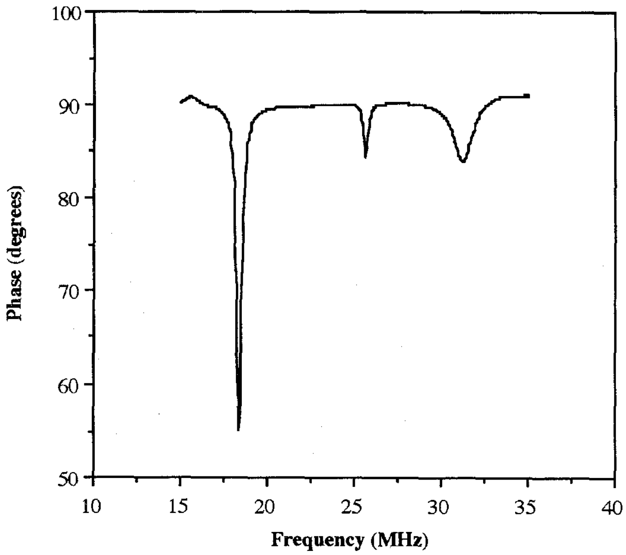

Figure 12. Array of three pressure sensors, each with different center frequency, as interrogated by a single antenna.

CONCLUSIONS

The design, modeling, fabrication and testing of a wireless ceramic sensor are presented. The sensor is made from ceramic co-fired tape to create a sealed cavity structure with a flexible ceramic membrane. The ceramic structure is integrated with a varying C/fixed L resonant circuit. The resonant frequency of the sensor shifts with applied pressure. A passive wireless scheme is used to retrieve the pressure data. Results of pressure and temperature tests are presented and show that this concept is valid. The theoretical model compares well the measured data where the theoretical sensitivity is 2.2MHz/bar and the measured sensitivity is 2.6MHz/bar. An experiment demonstrating the feasibility of reading out an array of sensors is also presented. Further sensor work involves redesigning the sensor structure to place the metal electrodes of the capacitor inside the sealed cavity and to encapsulate the coil and interconnecting via with ceramic to form a self-packaged device.

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