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A Ceramic Capacitive Pressure Microsensor with Screen- Printed Diaphragm

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ABSTRACT

In this research, new thick film screen-printed ceramic microsensors have been proposed, developed, and characterized as discrete devices for high temperature applications and as sensors for smart ceramic packaging applications.

In realizing thick film ceramic microsensors, a new substrate fabrication technique using thick film screen-printed sacrificial layers to create ceramic diaphragm microstructures has been developed. Previously reported ceramic microsensors were primarily focused on Low Temperature Co-Fired Ceramic (LTCC) substrate fabrication technology, but this new thick film substrate fabrication technology offers many advantages over LTCC. The main advantage is screen print selectable cavity airgap distance and diaphragm thickness.

A ceramic cavity microstructure has been designed and fabricated. In order to evaluate the limitations of sensors types that can be produced with this new substrate fabrication technique, the ceramic cavity was fully characterized for hermeticity.

Ceramic capacitive pressure microsensors have been fully developed and realized in this work. The pressure microsensor design, simulation, fabrication and characterization have been completed. The pressure microsensor shows excellent pressure sensitivity.

To demonstrate the flexibility of this microfabrication technique, a piezoresistive sensor was also designed, fabricated and characterized.

Additionally an integrated substrate that consisted of both types of sensors – capacitive and PZR was fabricated and characterized. This developed capability of

fabricating multiple types of sensors with thick film enables smart ceramic packaging. This capability allows monitoring of the microelectronic module's environment and permits compensation where necessary to maintain device reliability. To demonstrate this smart ceramic packaging capability, a prototype microelectronic module containing a capacitive pressure microsensor was created in this work. Monitoring of an imbedded pressure microsensor would indicate loss of package hermeticity and would enable device environment recovery methods.

In conclusion, new ceramic capacitive pressure and piezoresistive stress microsensors have been developed utilizing a new thick film substrate fabrication technique. The new thick film sensors and fabrication technique can be used to manufacture stand-alone discrete sensor devices for high temperature harsh environment applications. Additionally, the fabrication technique can be utilized to create imbedded sensors in the thick film microelectronics module substrate for a wide variety of high reliability smart ceramic packaging applications.

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A CERAMIC CAPACITIVE PRESSURE MICROSENSOR WITH SCREEN-PRINTED DIAPHRAGM

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LIST OF SYMBOLS

C	Capacitance
ϵ_0	Permittivity of free space
ϵ_r	Relative dielectric constant
A	Area of electrodes
d	Electrode separation distance
D	Flexural rigidity
E	Young's Modulus
h	Diaphragm thickness
ν	Poisson's ratio
R_l	Measured leak rate of tracer gas (He) through the leak in atm cc/s He
L	Equivalent standard leak rate in atm cc/s Air
P_E	Pressure of exposure in atmospheres absolute
P_O	Atmospheric pressure in atmospheres absolute
M_A	Molecular weight of air in grams (28.7)
M	Molecular weight of the tracer gas (He) in grams (4)
t_l	Time of exposure to P_E in seconds
t_2	Dwell time between release of pressure and leak detection in seconds
V	Internal volume of the device package cavity in cubic centimeters
P	Pressure
a	Diaphragm width
α_1, α_2	Rectangular geometry coefficients

w_o	deformation at the diaphragm center
C_{eff}	Effective capacitance
C_T	Top dielectric capacitance
C_A	Airgap capacitance
C_B	Bottom dielectric capacitance
d_T	Top dielectric thickness
d_A	Airgap thickness
d_B	Bottom dielectric thickness
C_{eq}	Equivalent capacitance
C_S	Stray capacitance
d_S	Electrode separation distance for stray capacitance
R	Resistance
P	Sheet resistivity
L	Resistor length
W	Resistor width
t_F	Thickness factor

CHAPTER 1

INTRODUCTION

1.1 Research Motivation

The objective of this research was to develop a novel thick film screen-printing fabrication technique to create ceramic microstructures. The newly developed thick film fabrication technique was utilized to create a ceramic cavity enabling the development of new forms of discrete thick film ceramic sensors. A discrete ceramic capacitive pressure microsensor with screen-printed diaphragm was realized using this novel technique. In addition, utilizing this developed thick film fabrication method provides for smart ceramic packaging where thick film sensors may be imbedded into the microelectronics ceramic packaging substrate.

The primary motivation for this research is to enable robust smart microelectronic packaging. Smart microelectronic packaging would create devices capable of operating under harsh conditions such as large temperature or pressure excursions, high g-forces, etc., while maintaining excellent performance and stability characteristics.

The implementation of smart packaging has three primary challenges. The first challenge is to enhance the robustness of the packaging to provide immunity to environmental changes. The second challenge is to monitor the packaging environment using imbedded sensors. The third challenge is to use the imbedded sensor output signals

to activate environmental control and in-situ repair mechanisms to provide long-term device performance and stability.

An example of a device application that would benefit from smart packaging is MEMS (Microelectromechanical Systems) gyroscopes. MEMS gyroscopes are typically resonating structures that utilize a proof mass. For optimum performance, these MEMS devices must be packaged in a vacuum environment in order to avoid viscous dampening of the resonating structure. Smart packaging would incorporate pressure sensors to monitor the internal package pressure. If the vacuum packaging begins to lose integrity, a pressure control circuit could enable activation of an in-situ getter vacuum pump to re-establish and maintain the internal vacuum environment. Also, the bias stability of MEMS gyroscopes is strongly influenced by packaging stress. Smart packaging with imbedded stress sensors could activate SMA (Shape Memory Alloy) mechanical elements to counteract the externally applied stresses.

Another smart packaging device application is data telemetry transmitter modules that are used jet engine testing applications. These hermetic telemetry modules are often transmitting critical sensor data. These modules must be hermetic such that external liquids such as engine oil or cooling fluids which do not penetrate the packaging and corrode the internal components. Imbedded smart sensors could monitor the internal package pressure to indicate the status of the package hermeticity. Based on the hermeticity status, a judgment can be made on the reliability of the transmitted data.

In support of the above motivation, this research focused on developing a packaging fabrication technology that is: (1) based on a robust materials system and (2) is capable of

creating sensors suitable for harsh environments that can be imbedded in the device packaging.

Pressure microsensors are typically made of silicon and rely on piezoresistive and capacitive sensing techniques. For harsh environment applications, silicon is not an ideal choice due to material property degradation at high temperature. Silicon undergoes creep under minimal load at temperatures greater than 500 °C [1-4]. Also, the majority of silicon pressure sensors utilize piezoresistive sensing techniques which inherently have a strong temperature dependence due to the temperature coefficients of the doped resistors [5-9]. As alternatives to silicon for harsh environments sensing applications, many high-temperature materials such as polycrystalline diamond [10-12] and silicon carbide [1,2,14-15] have been investigated as alternatives to silicon. Microfabrication techniques with these two materials are still immature although silicon carbide is making great progress [16-18]. Ceramic materials offer excellent high temperature properties and have also been investigated but the research has been primarily focused on Low Temperature Co-fired Ceramic Technology (LTCC) [19-22] as the device microfabrication technique. However, in the microfabrication of sensors and actuators, ceramic thick film screen-printed on alumina offers many advantages over LTCC in terms of thermal conductivity, mechanical strength, and Young's Modulus. The biggest functional advantage of ceramic thick film when creating cavities for sensors is print selectable cavity airgap distance and diaphragm thickness. With LTCC, the dielectric tapes are manufactured to predetermined thicknesses with the minimum fired thickness being approximately 94 μm . This limits the sensor designer's ability to control the sensitivity of the device. Thick film on alumina offers greater sensor design flexibility due to the fact that the dielectric

layers are screen-printed. Screen-printing of the dielectric layers permits variation of the cavity airgap distance and diaphragm thickness over a much wider range by adjusting screen-print parameters such as screen mesh count, squeegee pressure and speed.

1.2 Review of Previous Work

There has been an abundance of research focused on silicon based pressure micro sensors [23-25]. Recently M. Suster et al created a silicon pressure microsensor with a 0.8 mm diameter diaphragm [5]. Their device relied on capacitive sensing and is shown in Figure 1.1 below.

Figure 1.1 Silicon pressure microsensor [5].

Their device was remotely powered by use of an external laser. The device showed a sensitivity of 221 fF/psi. The pressure versus capacitance graph is shown in Figure 1.2 below. Elevated temperature data was not shown.

Figure 1.2 Capacitance versus absolute pressure [5].

As stated previously, many alternative materials for harsh environment applications have been recently investigated including silicon carbide (SiC), polycrystalline diamond, and ceramic.

Silicon Carbide has been studied as an alternate material to silicon for high temperature applications [1,2,14-18]. R. Okojie et al created a silicon carbide pressure sensor that relied on piezoresistive sensing techniques [1]. A schematic of their device is shown in Figure 1.3 below.

Figure 1.3 Silicon carbide pressure sensor [1].

The piezoresistors were extremely sensitive to temperature. The Temperature Coefficients of Resistance (TCR) for the devices produced were -3.07 %/100 °F at 180 °F and 4.24 %/100 °F at 500 °F. The TCR switches from a negative value to a positive one as the scattering switches from impurity to thermal. Due to the high temperature sensitivity of the piezoresistors, thermal compensation was necessary.

Polycrystalline diamond has also been studied as an alternate harsh environment sensor material [10-12]. E. Obermeier et al created a device with boron doped polydiamond piezoresistors [10]. Their device is shown in Figure 1.4 below. The device has diaphragm dimensions of 1.3 mm x 1.3 mm. The diaphragm thickness was 30 μm .

Figure 1.4 Boron doped polydiamond piezoresistive pressure sensor [10].

No performance data was provided in the referenced papers. Their work uncovered many problems with polycrystalline diamond including: reproducibility and surface roughness of the diamond films, reliable ohmic contacts, and passivation processes. Obermeier's research focus switched to SiC.

K. Holmes et al also researched polycrystalline diamond [11]. The devices they developed had a diaphragm diameter of 0.75 mm and a thickness of 14 μm . A few device configurations were attempted and are shown in Figure 1.5 below.

Figure 1.5 Polycrystalline diamond pressure sensor [11].

Piezoresistive sensing was utilized. Only room temperature data was published. The stated sensitivity was 0.13 mV/psi.

Ceramic materials have also been investigated for harsh environments. M. Allen et al created a wireless ceramic pressure sensor using Low Temperature Co-fired Ceramic technology [19-20]. Their device had a 8.4 mm diameter and a diaphragm thickness of 100 μm . Capacitive sensing was utilized. The device, shown in Figure 1.6 below, was made wireless by incorporating an inductor coil. The LC circuit's resonant frequency changed with changes in applied pressure.

Figure 1.6 LTCC capacitive pressure sensor (a) schematic cross section, (b) layered construction, and (c) top-view photograph of a ceramic pressure sensor with silver screen printed conductors [19].

The sensitivity data they collected was resonant frequency change versus applied pressure and is shown in Figure 1.7 below.

Figure 1.7 Resonant frequency versus pressure [19].

Although this device was wireless, a surrounding antenna was required to pick-up the resonant frequency change.

In addition, M. Zarnick et al have also studied the modeling of LTCC structures versus experimental results [21-22]. The device structure they created was based on piezoresistive sensing. The testing device is shown in Figure 1.8 below.

Figure 1.8 LTCC Piezoresistive pressure sensor [21].

Their study verified that the maximum resistance change occurred in the center of the diaphragm where the maximum tensile strain occurs. Their work also concluded that LTCC material property data needed to be further characterized. See Figure 1.9 below.

Figure 1.9 Resistance change versus resistor location [21].

1.3 Research Objectives

The major objective of this work was to create a thick film screen-printed ceramic pressure microsensor for harsh environment applications. The end goal was to develop an enabling microfabrication technology toward smart ceramic packaging. As a means to this end, thick film substrate fabrication technology was combined with MEMS fabrication techniques to create the desired thick film screen-printed ceramic sensor devices.

The first objective was to develop new thick film processing techniques to create a ceramic cavity with a screen-printed diaphragm. The ultimate goal of this first objective was for the cavity to have excellent hermeticity so that sensors requiring a reference cavity atmosphere could be realized. The design, fabrication and characterization of the newly developed ceramic cavity will be fully described in Chapter 3.

The second objective was to utilize this novel thick film screen-printed ceramic cavity as the fundamental microstructure for creating thick film ceramic microsensors. The first

thick film ceramic microsensor created in this work was a capacitive pressure microsensor. The capacitive pressure microsensor was designed and fabricated. In order to demonstrate usefulness as a sensing device, pressure and temperature characterization was performed. Chapter 4 describes the pressure microsensor design, fabrication and characterization.

Lastly, in order to demonstrate the flexibility of the newly developed microstructure, a second discrete thick film screen-printed microsensor was created in this work - a piezoresistive (PZR) stress sensor. The PZR stress sensor was fabricated and characterized for sensitivity to applied stress. After successful demonstration of the above, thick film substrates were fabricated which incorporated both types of sensors: capacitive pressure and PZR stress. Finally, a fabricated capacitive pressure microsensor was installed in a prototype microelectronic module. A module hermeticity monitoring characterization was performed utilizing the fabricated sensor. The successful demonstration of integrated pressure and stress sensors and module hermeticity monitoring characterization fully enables smart ceramic packaging. Chapter 5 discusses these smart packaging results. In addition, an application using smart ceramic packaging will also be described in Chapter 5.

Finally, research accomplishments and contributions will be summarized in Chapter 6. The potential future work will also be suggested.

CHAPTER 2

CERAMIC MICROSTRUCTURES

2.1 Introduction

Ceramic microstructures have been studied extensively. Ceramic materials offer exceptional mechanical, electrical and thermal properties that make them an ideal material choice for MEMS devices. Ceramic microfabrication techniques have firing temperatures of greater than 800 °C. These high temperature characteristics make them an excellent choice for harsh environment sensor devices. The basic ceramic materials used in the microelectronic industry will be reviewed. Ceramic microfabrication technologies common to the microelectronics industry will also be discussed and compared. Lastly, work in the area of ceramic pressure microsensors will be reviewed.

2.2 Ceramic Materials

There are a wide variety of ceramic materials that have excellent high temperature properties. The hybrid microelectronics industry uses ceramic substrates as both a mechanical base to support the many components (resistors, capacitors, diodes, transistors, integrated circuits, ...) and as the main electrical interconnect between these components.

These ceramic substrates can be patterned via either subtractive or additive techniques. Subtractive patterning techniques can utilize a plethora of ceramic materials such as alumina (Al_2O_3), beryllia (BeO), aluminum nitride (AlN), sapphire and fused silica to name a few but by its very nature subtractive patterning does not lend itself to

creating microstructures. For additive patterning, such as thick film technology or Low Temperature Co-fired Ceramic (LTCC), the primary ceramic substrate materials used are 96 % alumina oxide (Al_2O_3), aluminum nitride (AlN) and beryllium oxide (BeO). A comparison of material properties is listed in Table 2.1 [26]. Additive patterning will be fully discussed in 2.3 below.

Table 2.1 Ceramic Substrate Material Properties [26].

Property	Al₂O₃	AlN	BeO	Units
Density	3.98	3.3	3.9	g/cc
Youngs Modulus	350	310	345	GPa
Flexural Strength	300	300	250	MPa
Thermal Conductivity	20-30	170-200	250	W/mK
TCE	6.5	4.5	7.6	ppm

BeO is used for high power applications due to BeO's excellent thermal conductivity of 250 W/mK. The downside to BeO is that BeO dust is considered toxic [27]. Therefore, it has to be handled with care especially when grinding, drilling and polishing processes are required. Military electronic devices containing BeO require special marking for this reason [28].

AlN is also used for high power applications. AlN has thermal conductivity nearly as high as BeO without the safety concerns but it too has a major drawback. Thick film ink systems that are compatible with AlN have not been fully developed. There are commercial AlN inks available from a few suppliers but they can suffer from layer adhesion problems resulting in low yield [29].

The majority of the hybrid microelectronic devices contain 96 % Al_2O_3 (alumina) because it has excellent mechanical, electrical, and thermal properties yet it is inexpensive and readily available. Alumina has been used for over 30 years and the thick

film ink systems are mature, well established, and commercially available from several suppliers.

2.3 Ceramic Microfabrication Technologies

As described in 2.2 above, in the manufacture of hybrid microcircuits, substrates are fabricated either subtractively or additively.

Subtractive patterning is typically realized through thin film substrate fabrication technology. With this method, ceramic substrate materials are metallized using vapor deposition and sputtering techniques [30]. After metallization, the substrates are patterned using photolithography and chemical etching processes. Thin film substrate fabrication has many drawbacks. The three main disadvantages are high cost, chemical waste disposal, and the inability to create multi-conductor layer substrates. This last disadvantage translates to low circuit density.

Additive patterning is typically realized through one of three fabrication techniques: High Temperature Co-fired Ceramic (HTCC), LTCC, and thick film on alumina. Table 2.2 compares material properties of these technologies [31-33]. There are many references discussing these techniques in great detail [34,35].

Table 2.2 Ceramic Microfabrication Material Properties [31-33].

Property	HTCC	LTCC	Thick Film	Units
Density	3.62	3.1	3.75	g/cc
Youngs Modulus	275	152	331	Gpa
Flexural Strength	443	320	400	Mpa
Thermal Conductivity	20.3	3	26	W/mK
TCE	6.57	5.8	6.4	ppm
Surface Finish	<45	<10	<35	microinches
Dielectric Constant (1MHz)	9.2	7.8	9.5	
Buried Conductor Resistivity	0.012	0.0035	<.005	ohm/sq
Typical Layer Thickness Range	.010 - .030	.0038 - .0085	.0016 - .002	inch
Camber	0.003	0.003	0.003	inch/inch
Insulation Resistance at 100 V DC	1 x 10 ⁹	1 x 10 ¹²	1 x 10 ¹²	ohm
Hermetic?	yes	yes	yes	
Firing Atmosphere	Reducing	Air	Air	
Integral Resistors?	no	yes	yes	

2.3.1 Thick Film on Alumina

In the thick film screen-printing on alumina process, a viscous thick film paste is forced through screen openings in order to deposit a pattern onto a substrate. The screen is a stainless steel wire mesh that is adhesively attached to a cast aluminum frame. A photosensitive emulsion is deposited on the underside of the screen. This emulsion is patterned using a photopositive mask. The mask is placed into direct contact with the screen emulsion and then is exposed to ultraviolet (UV) light. After exposure, the screen is rinsed in water. The areas not exposed to the UV light (dark areas on the mask) wash away and create openings in the screen.

In this process, a rubber blade called a squeegee is used to force the paste through the screen. The screen quality, paste rheology, and printer set-up are the three most important factors in creating a high quality thick film print. Figure 2.1 below demonstrates the thick film screen-printing process [36].

Figure 2.1 Thick film screen-printing process [36].

Thick film technology on alumina uses this screen-printing process to create conductor and via fill layers. Thick film is a serial process where individual layers are printed, dried, and fired in a sequential fashion. Unlike the two co-fired technologies described below, the thick film layers are screen-printed onto fired 96 % alumina substrate. Thick film dielectric inks are used to create the required insulation between conductor layers. These dielectric layers can be printed to practically any thickness with $40\text{ }\mu\text{m}$ being typical. The thick film inks used are fired in air atmosphere at $850\text{ }^{\circ}\text{C}$. Like LTCC technology, thick film on alumina utilizes low resistivity conductors and integral thick film resistors may be incorporated. Thick film on alumina has many material property advantages over the co-fired counterparts including higher thermal conductivity and Young's Modulus. One of the main drawbacks of thick film is layer count. Substrate yields suffer beyond 7 conductor layers [35].

2.3.2 High Temperature Co-fired Ceramic (HTCC)

HTCC technology uses thick film screen-printing on unfired ceramic green tapes [35]. See Figure 2.2 for an overview of the HTCC process flow [34]. In HTCC, the individual circuit layers are screen-printed onto the green tape layers in parallel. HTCC tapes come in a variety of thicknesses ranging from 150 – 500 μm . The tapes are punched to form vias. Vias are filled by screen-printing. The individual layers are then stacked, aligned and laminated. Then the outer edges of the tape are cut to size. The laminated tape stack is then co-fired in a reducing atmosphere at approximately 1600 °C. One of the substantial advantages of HTCC technology is that multiple conductor layer (>20) substrates are achievable with high yield. Due to the high firing temperature, refractory metal conductors such as tungsten and molybdenum must be used. Besides the large capital equipment investment necessary, one of the main drawbacks to HTCC technology is that these conductors have high resistivity. Another drawback to the high firing temperature is that integral screen-printed resistors are not possible.

Figure 2.2 HTCC Process [34].

2.3.3 Low Temperature Co-fired Ceramic (LTCC)

LTCC technology is very similar to HTCC except the green tape materials used have a higher glass content which allows a lower co-firing temperature of approximately 850°C. LTCC tapes are commercially available and come in a variety of unfired thicknesses ranging from 114 – 254 μm [32]. See Figure 2.3 for a diagram of the LTCC process flow [37].

Figure 2.3 LTCC Process [37].

The lower firing temperature permits the use of low resistivity thick film conductors such as gold and silver. The lower firing temperature also permits integral thick film resistors. Like HTCC, LTCC offers high layer counts at high yield but without the high conductor resistivity issue. Therefore, LTCC offers the high packaging density of HTCC technology without a few of the limitations. LTCC also requires a large capital investment. Some of the other drawbacks to LTCC technology are X, Y, and Z shrinkage, poor thermal conductivity, and lower mechanical strength. The lower thermal conductivity and strength are inherent in the material due to the higher glass content.

2.4 Ceramic Pressure Microsensors

The majority of research in ceramic pressure microsensors has been focused on LTCC technology [19-22]. The primary reason being that LTCC technology has become

well established in the telecommunications and automotive industries due to the high conductor layer counts that are achievable at a reasonable yield and cost. Also, cavity structures are relatively easy to create by simply punching holes in the tape layer. Thick film on alumina technology offers many material property advantages as demonstrated in Table 2.2. The biggest advantage thick film technology offers over LTCC and HTCC when creating microsensor cavities is print controllable cavity depth and diaphragm thickness. LTCC and HTCC tapes are offered in standard unfired thicknesses. An example is DuPont 951 Low Temperature Co-fired Dielectric Tape that is offered in thicknesses of 114, 165, and 254 μm [32]. The 114 μm tape thickness reduces to approximately 94 μm after firing. Therefore, cavity airgap distances and diaphragms created with these tapes are limited to these fired thicknesses or multiples thereof.

For capacitive sensing techniques, the cavity airgap distance is critical because it is a major factor in determining the static device capacitance by the relation [38]

$$C = \frac{\epsilon_o \epsilon_r A}{d} \quad (1)$$

, where ϵ_o is the permittivity of free space, ϵ_r is the relative dielectric constant of the LTCC tape (7.8 for DuPont 951 Green Tape), A is the electrode area and d is the electrode separation distance, which is determined by the cavity airgap distance and the thickness of the dielectric layers. In LTCC technology, due to the nature of the green tapes used, d has a fixed minimum value. Therefore, in order to achieve reasonably measurable device static capacitance values, the electrode area and hence the overall device dimensions are limited. This factor limits the miniaturization of LTCC devices that use capacitive sensing techniques.

The thickness of the diaphragm impacts the flexural rigidity D of the microstructure by the relation

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad (2)$$

, where E is the Young's modulus, h is the diaphragm thickness, and ν is Poisson's ratio for the ceramic material [39]. Device designers using LTCC technology are limited by the tape thicknesses that translate to fixed h values. For high sensitivity microstructures where a thin diaphragm is required, designers are faced with a 94 μm thickness lower limit in LTCC technology. In HTCC technology, the problem is even worse with a minimum tape thickness available of 150 μm . In thick film technology, the cavity airgap distance and diaphragm thickness is variable by selection of the screen mesh, squeegee pressure and stroke speed that are used to print the dielectric diaphragm layer. Therefore, cavity and diaphragm designs of a wide range of depths and thicknesses are achievable.

2.5 Conclusions

For the reasons described above, ceramic materials are an excellent choice for creating microstructures for micro sensing applications. Ceramic has low density, high flexural strength, high Young's Modulus, high thermal conductivity and low temperature coefficient of expansion. There are many microelectronic substrate fabrication processes available to create micro electro mechanical structures. The three main multi-layer processes are thick film, HTCC and LTCC. Of these fabrication techniques, thick film screen-printing on alumina offers the best combination of material properties and sensor design flexibility. Ceramic pressure microsensors have been widely researched and studied but most of the work has been focused on LTCC due to the ease of creating cavities with this fabrication technology.

CHAPTER 3

DEVELOPMENT OF CERAMIC CAVITY

3.1 Introduction

In order to create a screen-printed thick film ceramic sealed gauge pressure microsensor, a new microstructure was developed. After considering many options, the MEMS fabrication technique of using a sacrificial layer was studied. The idea was to screen-print thick film dielectric layers over a sacrificial layer that would be subsequently chemically removed resulting in a cavity.

3.2 Design and Fabrication

The design objective was to create a sealed cavity that could be used to make a sealed gauge ceramic pressure microsensor for harsh environment applications. The initial stage of the design required the selection of a substrate material. 96 % Al_2O_3 was chosen for its wide application in the hybrid microelectronics industry. For physical dimensions, a 1.00" x 1.00" x 0.025" substrate size was chosen as it is an industry standard making the substrate low cost. Also, in order to minimize cost, the substrate was designed multi-up such that 10 sensors could be batch fabricated on the same substrate. In order to create a sealed ceramic cavity, a thick film etchable gold sacrificial layer was utilized. The separation distance of the desired cavity airgap was controlled by the thickness of the sacrificial layer print. One of the primary challenges was chemical etchant access to the sacrificial layer while maintaining the capability to seal the cavity. To enable access, laser drilled thru-ceramic vias were designed. Each device was designed with a 3 x 5

array of vias. These vias had to be large enough to permit flow of the etchant to the sacrificial layer yet small enough that they could be subsequently sealed by screen-printing thick film dielectric ink. The vias were designed for a diameter of 0.010". Figure 3.1 shows the ceramic substrate design.

Figure 3.1 Ceramic substrate design.

Due to limitations of the laser, the thru-ceramic via slightly tapers as it goes through the thickness of the ceramic. In order to optimize the flow of chemical etchant to the sacrificial layer, the sacrificial layer was printed on the smaller end of the taper as shown in Figure 3.2. In the remaining figures the slight taper will not be shown.

Figure 3.2 Cross-sectional view of via taper.

When choosing a fabrication technique, thick film on alumina was chosen because of the many advantages listed in Chapter 2. The only variation from standard thick film technology processing was the new development of using the sacrificial layer to create the cavity microstructure.

A schematic cross-sectional view of the device cavity prior to sacrificial layer removal is shown in Figure 3.3.

Figure 3.3 Cavity cross-sectional view prior to etch.

Figure 3.4 shows the cavity cross-sectional view after sacrificial layer removal.

Figure 3.4 Cavity cross-sectional view after sacrificial layer removal.

The detailed fabrication steps are shown schematically in Figure 3.5.

Figure 3.5 Ceramic cavity fabrication steps.

In Step 1, the alumina substrate is laser drilled to form the thru-ceramic vias. In Step 2, the thick film etchable gold sacrificial layer is screen-printed, dried and fired onto the

substrate. In Step 3, the dielectric diaphragm layer is screen-printed, dried and fired over the sacrificial layer. In Step 4, an etchant is used to chemically remove the sacrificial layer. Following sacrificial layer removal, a sealing dielectric layer is screen-printed, dried, and fired onto the backside of the substrate. Sacrificial layers thicknesses (SLTs) of 12 and 22 μm were used to fabricate cavities.

A cross-section microphotograph of the resulting cavity is shown in Figure 3.6.

Figure 3.6 Ceramic cavity micro-section.

Figure 3.6 clearly shows successful fabrication of the ceramic cavity and sealing of the thru-ceramic vias by the backside dielectric print.

3.3 Flexible Leak Test Methods

MIL-STD-883 Test Method 1014 Seal [40] was used to characterize the hermeticity of the cavity. For fine leak measurement, the test method offers several test conditions to use. The device under test is placed in a sealed chamber that is then pressurized with a tracer gas of 100 +0, -5 percent helium for the required time and pressure. The pressure is then relieved and the device is transferred to a second chamber that is connected to an evacuating system and a mass-spectrometer-type leak detector. When the chamber is evacuated, any tracer gas that was previously forced into the device cavity is drawn out and indicated by the leak detector as a measured leak rate. The time between release of tracer gas pressure and leak detection is defined as the dwell time. Since this cavity was uniquely small, the flexible method test condition A₂ was chosen. In the flexible method, the device cavity volume (V), the bomb exposure pressure (P_E), exposure time (t₁), and dwell time (t₂) are variables that can be input to the following formula from MIL-STD 883 Test Method 1014 Seal to calculate the maximum measured leak rate.

$$R_1 = \frac{LP_E}{P_0} \left(\frac{M_A}{M} \right)^{\frac{1}{2}} \left\{ 1 - e^{-\left[\frac{LT_1}{VP_0} \left(\frac{M_A}{M} \right)^{\frac{1}{2}} \right]} \right\} e^{-\left[\frac{LT_2}{VP_0} \left(\frac{M_A}{M} \right)^{\frac{1}{2}} \right]}$$

Where:

- R₁ = The measured leak rate of tracer gas (He) through the leak in atm cc/s He.
- L = The equivalent standard leak rate in atm cc/s air.
- P_E = The pressure of exposure in atmospheres absolute.
- P₀ = The atmospheric pressure in atmospheres absolute. (1)
- M_A = The molecular weight of air in grams. (28.7)
- M = The molecular weight of the tracer gas (Helium) in grams. (4)
- t₁ = The time of exposure to P_E in seconds.
- t₂ = The dwell time between release of pressure and leak detection, in seconds.
- V = The internal volume of the device package cavity in cubic centimeters.

The maximum equivalent standard leak rate (L) for this size device cavity is 5×10^{-8} atm cc/s air. The internal cavity volume (V) was calculated to be 0.000176 cc and 0.000324 cc for the 12 and 22 μm sacrificial layer thicknesses (SLT) respectively. The exposure pressure (P_E) was 30 PSIA, the exposure time (t_1) was 3 hours, and the maximum dwell time (t_2) was 1 hour. Using the above formula and the applied test conditions, the maximum acceptable measured leak rate R_1 , was calculated to be 1.8×10^{-8} atm cc/s He and 6.1×10^{-8} atm cc/s He for the 12 and 22 μm SLTs respectively.

3.4 Experimental Results for Hermeticity

The devices were characterized for hermeticity using the test method described previously in Section 3.3. The hermeticity results have been described [41]. In order to evaluate the cavity for harsh environment applications, the testing was performed after 1, 2, 4, and 8 hour exposures to temperatures of 100 °C, 300 °C, and 500 °C. In order to characterize the amount of helium adsorbed on the device surface, devices without a cavity were also tested for benchmark comparisons. Empty test fixture background readings were taken to characterize the amount of helium previously adsorbed on the test fixture walls and the amount of helium present in the ambient air. The 100 °C data is graphed in Figure 3.7.

Figure 3.7 Hermeticity versus exposure time, 100 °C.

The maximum measured leak rates after exposure to 100 °C were 6.9 and 7.0 $\times 10^{-10}$ atm cc/s He for the 12 and 22 μm SLTs respectively. These measured leak rates are very low and are well below the calculated limits of 1.8×10^{-8} atm cc/s He and 6.1×10^{-8} atm cc/s He respectively.

The 300 °C data is graphed in Figure 3.8.

Figure 3.8 Hermeticity versus exposure time, 300 °C.

The maximum measured leak rates after exposure to 300 °C were 4.0 and 5.2×10^{-10} atm cc/s He for the 12 and 22 μm SLTs respectively. These measured leak rates are also very low and are well below the calculated limits of 1.8×10^{-8} atm cc/s He and 6.1×10^{-8} atm cc/s He respectively.

The 500 °C data is graphed in Figure 3.9.

Figure 3.9 Hermeticity versus exposure time, 500 °C.

The maximum measured leak rates after exposure to 500 °C were 3.8 and 4.6×10^{-10} atm cc/s He for the 12 and 22 μm SLTs respectively - well below the limits.

3.5 Conclusions

As can be seen from the data and graphs from 3.4 above, the fabricated ceramic cavities were very hermetic with maximum measured leak rates of 6.9 and 7.0×10^{-10} atm cc/s He for the 12 and 22 μm SLTs respectively. These leak rate values are well below the hermetic maximum values defined and calculated in 3.3 above of 1.8 and 6.1×10^{-8} atm cc/s He. This excellent hermeticity characteristic of the fabricated ceramic cavity makes the cavity an ideal microstructure for sealed ceramic pressure microsensor applications.

CHAPTER 4

CERAMIC PRESSURE MICROSENSOR

4.1 Introduction

The objective of this work was to develop a pressure sensor suitable for harsh environment applications. For the reasons outlined in Chapter 2, thick film on alumina was chosen for the ceramic pressure microsensor fabrication technology. In Chapter 3, the hermeticity data demonstrated this technology was capable of producing a sealed cavity that is the fundamental microstructure required for sealed gauge pressure sensor. When considering the different sensing techniques, capacitive sensing was chosen due to the fact that it is less susceptible to temperature effects. These criteria: thick film fabrication, sealed cavity microstructure, and capacitive sensing were the key inputs to the sensor design.

4.2 Design and Simulation

The goal of the design was to create a ceramic parallel plate capacitor with a top electrode that was on top of a ceramic diaphragm. As the diaphragm deflected under pressure changes, capacitance value changes would result by the general relation given in equation (1).

$$C = \frac{\epsilon_o A}{d} \quad (1)$$

, where C is the capacitance, ϵ_0 is the permittivity of free space, A is the area of the electrodes and d is the electrode separation distance. A schematic diagram of the sensor operation is shown in Figure 4.1.

Figure 4.1 Sensor schematic diagram.

As pressure increases, the top plate would deflect decreasing the value of d and resulting in an increase in the sensor capacitance. The opposite would be true of a pressure decrease.

The downward deflection is represented by equation (2) below [42]:

$$P = \frac{Eh^3}{(1-\nu^2)a^4} \left[\alpha_1 \frac{w_o}{3h} + \alpha_2 \frac{4w_o^3}{h^3} \right] \quad (2)$$

, where P is the uniform applied pressure, E is Young's modulus of the diaphragm material, h is the diaphragm thickness, ν is Poisson's ratio, a is diaphragm width, α_1 and

α_2 are the rectangular geometry coefficients and w_0 is the deformation at the diaphragm center. Figure 4.2 is a graph showing the deflection at the diaphragm center versus applied pressure.

Figure 4.2 Diaphragm deflection versus pressure.

In order to use the thru-ceramic via technique described in Chapter 3 to etch the sacrificial layer and create the cavity, the bottom electrode required holes. It was important to recess the bottom electrode away from the edges of the thru-ceramic via so that it would not be attacked by the chemical etchant. Also, a dielectric layer was necessary to cover the bottom electrode again to protect it from the chemical etchant. Figure 4.3 illustrates the bottom electrode recess.

Figure 4.3 Cross-sectional view of recessed bottom electrode.

A sacrificial layer was required to create the cavity and a top dielectric layer was required to protect the top electrode from the etchant. A termination material layer was required to facilitate device interconnection. Lastly, a dielectric layer was required for the backside of the substrate to create the final seal after etching. All layers were designed in AutoCad. A multi-up design was used such that 10 sensors would be batch fabricated on each alumina substrate.

The designed sensor outer dimensions were 0.310" x 0.150" x 0.025". The designed diaphragm area was 0.190" x 0.110". With thick film, the diaphragm thickness is variable but a thickness of 32 μm was initially chosen for the design and analysis.

In determining the theoretical calculated capacitance of the device, the dielectric materials must be taken into account. See Figure 4.4 for the illustration of the effective capacitance.

Figure 4.4 Sensor effective capacitance diagram.

In this case, the effective capacitance is determined by treating the device as three capacitors in series. Since capacitors in series have a reciprocal relation, the resultant effective capacitance is given by equation (3) below.

$$\frac{1}{C_{eff}} = \frac{1}{C_T + C_A + C_B} \quad (3)$$

, where C_{eff} is the effective capacitance, C_T is the capacitance of the top dielectric, C_A is the capacitance of the airgap, and C_B is the capacitance of the bottom dielectric. In Figure 4.2, d_T , d_A , and d_B are the thicknesses of the top dielectric, airgap, and bottom dielectric respectively.

To calculate the individual capacitances C_T , C_A , and C_B equations (4) through (6) are used.

$$C_T = \frac{\epsilon_o \epsilon_r A}{d_T} \quad (4)$$

$$C_A = \frac{\epsilon_o A}{d_A} \quad (5)$$

$$C_B = \frac{\epsilon_o \epsilon_r A}{d_B} \quad (6)$$

, where ϵ_o is the permittivity of free space and ϵ_r is the relative dielectric constant of the dielectric material.

4.3 Fabrication

A schematic of the fabrication steps is shown in Figure 4.5 below.

Figure 4.5 Sensor fabrication steps (illustration).

In order to realize the design, some thick film fabrication tools were necessary. These tools consisted of layer artwork, screens, and print fixtures.

The individual layers were created in AutoCad using standard thick film design rules. The artwork for the individual layers was created from the AutoCad design files. The AutoCad files were used to create 15X plots of the layers. These layers were then reduced to 1:1 glass masks using a light table. A sample mask is shown in Figure 4.6 below.

Figure 4.6 Example 1:1 glass mask.

From these masks, screens were created by an ultraviolet light exposure process. A sample screen is shown in Figure 4.7.

Figure 4.7 Example screen.

In order to hold the substrate during the screen-printing process a print fixture needed to be made. This print fixture had to have a milled out vacuum cavity so that when the substrate was flipped over to print the backside sealing dielectric, the microstructure on the top side of the substrate would not be damaged. The print fixture is shown in Figure 4.8 below.

Figure 4.8 Vacuum print fixture.

Once these fabrication tools were created. The fabrication process began. The individual steps are shown in Figure 4.9 below.

Figure 4.9 Sensor fabrication steps (photographs).

One of the critical fabrication steps was the blind etching of the sacrificial layer. In order to establish this process, etch set-up samples with a clear top dielectric were fabricated along with the real devices. The clear dielectric allowed visual feedback to the etching process. Once the process was established with the set-up pieces, the real devices were exposed using the determined etching process parameters. An example of the etch set-up samples is shown in Figure 4.10 below.

Figure 4.10 Etch set-up pieces.

The singulated ceramic capacitive pressure microsensor is shown in Figure 4.11 below.

Figure 4.11 Singulated ceramic capacitive pressure microsensor.

4.4 Experimental Results

4.4.1 Micro-Section Analysis

The first characterization step was to micro-section some of the fabricated sensors to validate that the blind etching of the sacrificial layer was successful. Figure 4.12 below shows a micro-section of a sensor that has not been etched.

Figure 4.12 Pressure sensor thick film layer micro-section (pre-etch).

Figure 4.13 below shows a sensor after etching. It is clear from the photograph that both electrodes are present and that the sacrificial layer has been removed resulting in a cavity.

Figure 4.13 Pressure sensor thick film layer micro-section (post-etch).

4.4.2 Pressure versus Capacitance

The second step in characterizing the fabricated pressure microsensors was to measure their static room temperature capacitance and compare that against the theoretical value. Capacitance measurements were made on 12 and 22 μm sacrificial layer devices using an Agilent 4284A LCR meter. The average measured capacitance values for the 12 and 22 μm devices were 8.1238 pF and 5.9647 pF respectively. Using equation (3) from Section 4.2 above, the initial calculated theoretical values were 7.3543 pF and 4.6283 pF which were lower than the measured values. In order to analyze the difference, additional micro-sections were performed on several devices. The micro-sections revealed small stray capacitances which are shown in Figure 4.14 that needed to be taken into account.

Figure 4.14 Stray capacitance micro-section.

Three primary stray capacitances were identified and are illustrated in Figure 4.15 below.

Figure 4.15 Stray capacitance illustration.

These capacitances are in parallel with the effective capacitance (C_{eff}) defined in equation (3) above. The resulting equation (7) is given below.

$$C_{eq} = C_{eff} + C_{s1} + C_{s2} + C_{s3} \quad (7)$$

Using equation (7) to account for the stray capacitances, the theoretical calculated capacitances were 7.9672 pF and 5.2412 pF for the 12 and 22 μm sacrificial layer thicknesses. These calculated values are in very close agreement with the average measured values stated above of 8.1238 pF and 5.9647 pF.

After the static room ambient temperature and pressure values were characterized, the fabricated pressure microsensors were tested for their response to applied pressure. Measurements were made for devices with 12 and 22 μm sacrificial layers. The test was repeated to demonstrate repeatability. The testing apparatus consisting of an Agilent 4284A LCR Meter, bomb chamber, and digital pressure gauge are shown in Figure 4.16.

Figure 4.16 Pressure versus capacitance testing apparatus, room temperature.

Figure 4.17 is a graph of the Pressure versus Capacitance data at room temperature.

Figure 4.17 Pressure versus capacitance at 25 °C.

The 12 and 22 μm sacrificial layer devices showed an average sensitivity of 11.5 and 22.0 fF/psi respectively. The 12 μm device showed excellent repeatability. The 22 μm device did not quite return to the original capacitance value after the first test indicating that the diaphragm did not regain its original position. The device was cross-sectioned and it was found that the diaphragm was only 20 μm thick. The thinner diaphragm dielectric print was caused by the thicker sacrificial layer. The same printer settings were used but since the 22 μm devices were higher in the z-axis direction on the printer stage a thinner dielectric print resulted. When the 20 μm diaphragm thickness is used in equation (2), the maximum diaphragm deflection at 60 psig increased to 13 μm . This was an additional deflection of approximately 22 % and caused a relaxation of the

diaphragm. When the 22 μm device was tested a third time, the data was very repeatable with the second test results.

In order to validate that the capacitance change was in fact due to the diaphragm deflection under pressure and not due to a cable or interconnection change with pressure, an unetched device was exposed to increasing pressure using the same interconnection cable and the capacitance change was measured. The result is shown in Figure 4.18. The capacitance changed minutely over the full pressure change with a somewhat random range of values varying from 15.8283 pF to 15.8292 pF which is a total capacitance change of only 0.9 fF over the entire pressure range of 0 to 60 psig. This result validates that the capacitance changes shown for the sensors in Figure 4.17 above were due to the diaphragm deflection under pressure.

Figure 4.18 Pressure versus capacitance unetched sensor.

Figure 4.19 below shows that the capacitance change tracks well with the calculated diaphragm deflection.

Figure 4.19 Pressure versus capacitance versus deflection, 12 μm SLT device.

In order to evaluate the sensor's performance in harsh environments, pressure versus capacitance testing was repeated on the 12 μm sacrificial layer device at elevated temperatures. The testing apparatus that consisted of an Agilent 4284A LCR meter, a Scientific Sealing Technology vacuum soldering chambers and digital pressure gauge are shown in Figure 4.20 below.

Figure 4.20 Pressure versus capacitance testing apparatus, elevated temperatures.

Figure 4.21 is a graph of the Pressure versus Capacitance data at elevated temperatures of 21 °C, 100 °C, 200 °C, and 300 °C.

Figure 4.21 Pressure versus capacitance, 21 °C, 100 °C, 200 °C, and 300 °C.

The 12 μm sacrificial layer device showed an average sensitivity of 9.2 fF/psi over the temperature and pressure ranges of 21 °C to 300 °C and 0 to 50 psig respectively. This elevated temperature and pressure sensitivity data is excellent and has been published [43].

4.4.3 Temperature Effect

The next characterization step was to measure the temperature effect on the capacitance value of the sensor. Figure 4.22 below shows the Temperature versus Capacitance data taken from 15 °C to 300 °C for the 12 µm sacrificial layer device.

Figure 4.22 Temperature versus capacitance, 15 °C to 300 °C.

The 12 µm sacrificial layer device showed an average temperature coefficient of 68.3 ppm/°C over the temperature range of 25 °C to 125 °C and 96.9 ppm/°C over the temperature range of 15 °C to 300 °C. These coefficients are excellent and fall between the general specifications of an NPO (+/- 30ppm/°C) and a BX or X7R (+/- 15 % maximum from -55 °C to +125 °C) dielectric capacitor.

In order to discern if the sensor TCC characteristic was due to the dielectric material properties or the microstructure itself, devices that were not etched and thus no cavity, were analyzed for TCC. The unetched sensors had a TCC of 138 ppm/°C over the range of 25 °C to 125 °C and 249 ppm/°C over the range of 25 °C to 300 °C. The data is graphed in Fig. 4.23.

Figure 4.23 Temperature versus capacitance data from 15 °C to 300 °C for unetched 12 μm SLT devices.

When this change is analyzed over these temperature ranges using equation (8) for a device with no cavity, the corresponding TCC values for capacitances C_T and C_B are also 138 and 249 ppm/°C over the temperature ranges of 25 °C to 125 °C and 25 °C to 300 °C, respectively.

$$\frac{1}{C_{eff}} = \frac{1}{C_T + C_B} \quad (8)$$

When these C_T and C_B TCC values are then inserted back into equation (3) and assuming C_A is unaffected by temperature change, the theoretical etched sensor with airgap TCC calculates to 49 ppm/°C over the range of 25 °C to 125 °C and 89 ppm/°C over the wider temperature range of 25 °C to 300 °C which is in close agreement with the measured sensor values stated previously in this section. This close agreement demonstrates that the sensor's TCC characteristic is primarily due to the dielectric material properties and is not the result of a physical microstructure change. It also shows the secondary benefit of the presence of the airgap – reduction of the device's temperature sensitivity. The sensor temperature effect data has been discussed [44].

4.5 Conclusions

Thick film ceramic capacitive pressure microsensors were designed, simulated and successfully fabricated. The resulting device microstructure formation was confirmed through micro-sectioning.

The sensors were fully characterized for pressure versus capacitance sensitivity at room and elevated temperatures. The microsensors showed excellent pressure response with an average sensitivity of 9.2 fF/psi at temperatures up to 300 °C.

The temperature effect coefficient was also determined and found to be 96.9 ppm/°C over the range of 15 °C to 300 °C. This temperature coefficient was very good and was determined to be a characteristic of the thick film dielectric material.

The characterization data demonstrates that the ceramic capacitive pressure microsensors created in this work are truly novel.

CHAPTER 5

SMART CERAMIC PACKAGING

5.1 Introduction

The end goal of this work was to demonstrate the feasibility of smart ceramic packaging where thick film sensors could be imbedded into the thick film ceramic interconnect substrate used in critical microcircuit module applications. Imbedded sensors in the substrate could indicate loss of module reliability through various mechanisms. The focus of this work was module reliability compromise due to loss of package hermeticity or stress induced effects. An imbedded stress sensor could indicate if the substrate is deflecting beyond the predicted design considerations which may cause damage to electrical components or interconnections. An imbedded pressure sensor could monitor package pressure to indicate if package hermeticity has been lost. A loss of package hermeticity may cause module failures. Many integrated circuits and MEMS devices are sensitive to moisture alone. Also, the combination of moisture and ionic contamination can cause corrosion of internal components such as aluminum bond pads on integrated circuits or thin film nichrome resistors. In a smart ceramic packaging module, if the imbedded sensor indicates a loss of hermeticity, a possible recovery mechanism could be the firing of an internal moisture getter [45]. This would be accomplished by driving an increased current through the package pins that the getter material is electrically connected to.

A diagram of a smart ceramic substrate for a Telemetry Transmitter Module is shown in Figure 5.1 as an example of such an application. The function of the Telemetry Module is to collect strain and temperature data and to RF transmit that data to a stationary data collection system. These telemetry modules are used in a wide range of applications to collect and transmit data off of rotating, mobile, and stationary systems. They are used in jet engine testing, train, racing sport, military, and aerospace applications. In the example of jet engine test telemetry modules, they are used specifically to collect engine qualification data. To set-up and run these engine qualification tests costs millions of dollars. Therefore, it is critical to know that the telemetry modules are transmitting reliable and accurate data. Smart ceramic packaging could incorporate pressure and stress sensors along with their associated signal conditioning and temperature compensation circuits, to indicate such a loss in reliability. The imbedded smart sensor inputs can be transmitted right along with the system sensor data and be retrieved at the ground receiver. Also, circuit performance changes could be compared against the sensor data to see if they were caused by environmental changes. Circuit compensation could be incorporated as a result to improve performance.

Figure 5.1 Smart data telemetry module interconnection substrate.

With this end goal in mind and the successful demonstration of a thick film ceramic pressure microsensor, work was undertaken to utilize the newly developed microstructure to create a micro PZR sensor. This effort was performed to demonstrate the sensor design flexibility of the microstructure. It was also necessary to show that both types of sensors could be integrated onto the same thick film substrate. Finally, to demonstrate the feasibility of integrating these sensors into a module, a prototype module was built which incorporated a capacitive pressure sensor. With these demonstrations completed - smart ceramic packaging will be fully enabled.

5.2 Piezoresistive Sensor

5.2.1 Design

To demonstrate the flexibility of the novel microstructure created in this work, a piezoresistive sensor was created using the same fabrication technique used to create the capacitive pressure sensor. The only major difference was that a thick film piezoresistor (PZR) was printed on top of the dielectric diaphragm in place of the top electrode in the capacitive sensing design. In pressure sensing applications the benefits of having the PZR sensor on the dielectric diaphragm are obvious. In stress sensing applications, the most straight-forward approach would be to deposit the PZR material directly on the ceramic substrate but in some stress sensing applications, there would be benefits to having the stress sensor slightly decoupled from the ceramic substrate in this fashion. In harsh environment, high stress applications, a PZR resistor printed directly on the substrate may suffer microcrack damage if the applied stress to the package is directly translated to the PZR sensor. A slightly decoupled PZR resistor on a diaphragm could still indicate applied stress to the package but the resistor itself would undergo a lower magnitude of stress.

The thick film PZR material chosen for this demonstration was DuPont 3554 Strain Gauge Resistor Ink [46]. This ink was developed to be screen-printed onto steel substrates for thick film strain gauge applications [47]. In these steel substrate applications, the substrate is first coated with an insulating dielectric prior to PZR material application by screen-printing. The ink contains RuO_2 and WO_3 conductive oxide particles in a vitreous borosilicate glass matrix. The main conduction mechanism

is electron tunneling between conductive grains through a dielectric matrix [48-49]. When printed to a dried thickness of 25 μm , 3554 has a typical sheet resistivity of 10 $\text{k}\Omega/\text{square}$ and a temperature coefficient of resistance (TCR) of ± 100 ppm [46].

The design of the proposed ceramic PZR sensor was realized. The resistor was designed to be 0.100" x 0.100" which is one square. The sensing mechanism occurs as applied stress causes a diaphragm deflection. This deflection results in a resistance change due to the piezoresistive effect.

As mentioned previously, the only modification to the capacitive pressure sensor design was that the thick film piezoresistor material was printed on top of the diaphragm in place of the top electrode. The resistor terminations were also slightly modified. The terminations needed to be gold to be compatible with the DuPont 3554 piezoresistive ink [46] and they needed to be printed under the piezoresistor. An illustration of the thick film PZR sensor is shown in Figure 5.2.

Figure 5.2 Thick film PZR sensor illustration (a) top view, (b) cross-sectional view.

5.2.2 Fabrication

The individual fabrication steps are similar to those used to create the capacitive pressure sensor and are shown in Figure 5.3 below. The main differences were that a

bottom electrode and dielectric were not necessary. All of the same screen-print and etch process parameters were utilized.

Figure 5.3 Thick film PZR sensor fabrication steps (a) laser drill holes, (b) print sacrificial layer, (c) print dielectric diaphragm, (d) print gold terminations, (e) print PZR resistor, and (f) etch sacrificial layer and print bottom dielectric.

Figure 5.4 below shows a photograph of an actual multi-up PZR sensor with screen-printed diaphragm.

Figure 5.4 Multi-up PZR sensor on screen-printed dielectric diaphragm.

5.2.3 Characterization

5.2.3.1 Static Resistance

Measurements of the static resistor value were performed for initial characterization of the proposed stress sensor. Theoretically the resistor value is determined by the relation given in equation (1).

$$R = \left(\frac{\rho L}{W} \right) * t_F \quad (1)$$

, where R = resistance in ohms, ρ = sheet resistivity, L = resistor length, W = resistor width, and t_F is the thickness factor. The thickness factor is a ratio of the actual dried print thickness to the theoretical dried print thickness stated for the sheet resistivity. The theoretical resistance calculated to be 3,533.21 ohms and the averaged measured for the fabricated devices was 3,585.67 ohms which is in very close agreement.

5.2.3.2 Stress versus Resistance

To evaluate usefulness as a stress sensor, applied stress versus resistance characterization has been performed on the PZR sensors. The devices were stressed from 0 to 300 gram force (2.94 Newtons) using the 3-point bend test illustrated in Figure 5.5 below.

Figure 5.5 Three-point bend test illustration

The sensor showed very good linearity over the range. The device sensitivity calculates to $-877 \text{ m}\Omega/\text{N}$. The minus sign indicates that the piezoresistor's value decreases with applied compressive force. This result is in complete agreement with similar research performed [50]. The test was performed a second time to show repeatability. The data is shown in Figure 5.6, which shows the negative resistivity of the PZR for increasing pressure.

Figure 5.6 Applied force versus resistance data for PZR sensor.

5.2.3.3 Pressure versus Resistance

To show usefulness as a pressure sensor, applied pressure versus resistance characterization was performed on the PZR sensors. The devices were pressurized from 0 to 60 psig using the same pressurization test set-up described in Chapter 4. The average device sensitivity was $-53.6 \text{ m}\Omega/\text{psi}$ and was fairly linear. The pressure versus resistance data is shown in Figure 5.7. Again, the negative resistivity of the PZR with applied compressive force characteristic is shown.

Figure 5.7 Applied pressure versus resistance data for PZR sensor.

5.2.3.4 Temperature Effect

The effect of temperature on the resistance of the PZR sensor was analyzed. As stated previously, the data sheet for the material states a TCR of ± 100 ppm [46]. PZR sensors were characterized for temperature versus resistance change from room up to 300 °C. The TCR of the sensors was -96.7 ppm/°C which meets the data sheet specification. In order to further characterize and discern if this measured resistance change was in fact due to the inherent TCR properties of the thick film PZR material and not a microstructure change with temperature – a sensor that had not been etched was also temperature characterized. The measured TCR for the unetched sensor was -112.4 ppm/°C which is in very close agreement with the measured sensor TCR of -96.7 ppm/°C.

ppm/ $^{\circ}\text{C}$. This close agreement suggests that there is no significant microstructure change in the temperature range of 25 $^{\circ}\text{C}$ to 300 $^{\circ}\text{C}$. The data is shown in Figure 5.8 and the graph shows that the two lines have very similar slopes.

Figure 5.8 Temperature versus resistance data for both an etched and unetched PZR sensors.

5.3 Smart Ceramic Packaging with Integrated Pressure Sensor

The second step to enable smart ceramic packaging was to integrate both types of sensors onto a single substrate to show that a multi-sensor type substrate could be produced. The third step was to create a prototype smart ceramic packaging module which incorporated the ceramic capacitive pressure sensor.

5.3.1 Integrated Sensor Substrate

The first demonstration step undertaken was to fabricate a thick film substrate which contained both types of thick film sensors – a capacitive sensor and a PZR sensor. An illustration of the integrated substrate is shown in Figure 5.9.

Figure 5.9 Integrated sensor substrate (illustration).

The fabrication of the substrate again followed the same fabrication steps outlined in 4.3 and 5.2.2. The fabricated integrated sensor substrate is shown in Figure 5.10.

Figure 5.10 Integrated substrate with capacitive and PZR sensors on screen-printed dielectric diaphragm (photograph).

In order to demonstrate functionality of the fabricated integrated substrate, stress versus resistance characterization using the 3-point bend test was performed as in 5.2.3.2 above. Resistance measurements off of the PZR sensor were taken as the applied force was increased from 0 to 3 Newtons and then decreased back down to 0 applied force. The device sensitivity was $-860 \text{ m}\Omega/\text{N}$. This sensitivity was in very close agreement with the measured sensitivity of $-877 \text{ m}\Omega/\text{N}$ reported for the multi-up PZR sensor characterized in 5.2.3.2. There was no evidence of hysteresis in the data. The data is shown Figure 5.11.

Figure 5.11 Stress versus resistance data for integrated sensor substrate.

5.3.2 Smart Ceramic Packaging Prototype

With the successful demonstration of the integrated sensor substrate, the last step to enable Smart ceramic packaging was to incorporate the previously fabricated ceramic capacitive pressure sensor into a microcircuit module. The pressure sensor was epoxy attached onto the module's thick film interconnect substrate and was electrically connected using 0.001" thermosonic gold wire bonds. A photograph of the prototype smart ceramic packaging module is shown in Figure 5.12.

(a)

(b)

Figure 5.12 Smart ceramic packaging module (a) full view (b) zoom view.

As stated previously in 5.1, a capacitive pressure sensor imbedded in the microelectronic module packaging substrate could indicate a reliability compromise due to loss of package hermeticity. High reliability microelectronic modules are sealed in a positive pressure seal chamber. The seal chamber environment is typically 90 % nitrogen and 10 % helium. The helium is included so that devices may be leak checked immediately after the sealing operation to verify hermeticity. The positive pressure can be maintained at a level of 5 psig. Therefore, when the module is hermetically sealed it would have a pressure differential of 5 psig with the external atmosphere. If the module package seal is compromised through physical damage, the internal pressure would leak up to the external atmospheric pressure – a change of 5 psig. To simulate this concept, the prototype smart ceramic packaging module was subjected to pressure versus capacitance testing at room temperature. For this characterization, the chamber pressure was held initially at 5 psig and then slowly released to 0 psig with sensor capacitance readings taken at 0.5 psig intervals. The pressure versus capacitance data is shown in Figure 5.13.

Figure 5.13 Applied pressure versus capacitance data for prototype smart ceramic packaging module.

The data was very linear with a sensitivity of -27 fF/psi over the range of 5 psig to 0 psig. This demonstration proves that the thick film capacitive pressure sensor can be utilized to monitor the package hermeticity. In a smart ceramic packaging module - a drop in the capacitance of the pressure sensor would indicate a loss of internal package pressure. Such an indication could trigger recovery mechanisms such as getter firing. Alternatively, in applications where redundant modules exist as is the case for jet engine testing data telemetry modules, this pressure loss indication would allow the test analysis personnel to disregard the data coming from the non-hermetic module.

5.4 Discussion and Conclusion

The benefits of smart ceramic packaging for high reliability applications have been posed. Implementation methods utilizing the novel thick film ceramic fabrication techniques developed in this work have been discussed. Applications for smart ceramic packaging have been shown and a specific real world example has been illustrated.

Multi-up thick film PZR sensors were fabricated onto a thick film dielectric diaphragm using the microstructure fabrication techniques that were used to create the ceramic capacitive pressure sensor. Characterization of the thick film PZR sensors showed their usefulness as both stress and pressure sensors. As a stress sensor, the devices had an average sensitivity of $-877 \text{ m}\Omega/\text{N}$. As a pressure sensor, the devices had an average sensitivity of $-53.6 \text{ m}\Omega/\text{psi}$. The temperature effect on the sensor was characterized and found to be $-96.7 \text{ ppm}/^\circ\text{C}$ which is consistent with the published data for the thick film PZR material.

To take the fabrication one step further, substrates with integrated thick film capacitive and PZR sensors were fabricated and characterized. The PZR stress sensor sensitivity on the integrated substrate was $-860 \text{ m}\Omega/\text{N}$ which was in close agreement with the measured sensitivity results for the discrete PZR stress sensor. This demonstration shows that thick film substrates can be manufactured with imbedded sensors of multiple sensing mechanism types.

Finally, a prototype smart ceramic packaging module was fabricated. A discrete thick film capacitive pressure sensor with screen-printed diaphragm was surface mount attached and wirebonded into a microelectronic module. The module was then placed

into a pressure chamber to simulate loss of package hermeticity. The capacitive sensor changed at a nearly linear rate of -27 fF/psi over the range of 5 psig to 0 psig. This prototype characterization displayed the benefits of the smart ceramic packaging concepts enabled by this work.

CHAPTER 6

CONCLUSIONS

6.1 Summary

In this thesis research, thick film on alumina ceramic microfabrication technology has been studied and extended for sensor applications. Two sensor application areas have been targeted to benefit from this research. The first application is discrete ceramic microsensors for high temperature applications. The second application is imbedded sensors for smart ceramic packaging.

Typical microsensor materials such as silicon have inherent material limitations that limit their usefulness for high temperature applications. Ceramic materials offer excellent thermal, electrical, and mechanical properties and can be utilized in high temperature applications. There are 3 mature ceramic microfabrication technologies that have been utilized in the microelectronics industry – High Temperature Co-fired Ceramic (HTCC), Low Temperature Co-fired Ceramic, and Thick Film on Alumina. Each has many positive features when being considered as a microelectronic interconnection substrate but for microsensor fabrication, this research shows that thick film on alumina has a distinct advantage – screen-print controllable cavity depth and diaphragm thickness. This thick film on alumina advantage permits greater sensor design flexibility which enables sensors for a wide variety of normal and harsh environment micro sensing applications.

In order to enable thick film sealed gauge ceramic microsensors, a novel thick film fabrication technique was developed in this work to create the required cavity microstructure. The technique involved standard thick film fabrication methods coupled with MEMS sacrificial layer fabrication techniques. The sealed ceramic cavity was designed. Devices were fabricated using sacrificial layer thicknesses (SLT) of 12 and 22 μm . Verification that the ceramic cavity was truly formed was proven through microsectioning techniques. In order to show usefulness of the microstructure for high temperature microsensing applications, characterization consisted of MIL-STD-883 Method 1014 hermeticity testing after elevated temperature exposures of 100 °C, 300 °C, and 500 °C. The maximum measured leak rates were 6.9 and 7.0×10^{-10} atm cc/s He for the 12 and 22 μm SLTs respectively. These leak rates proved to be excellent when compared against the calculated hermetic maximum values of 1.8 and 6.1×10^{-8} atm cc/s He.

The novel thick film fabrication technique was then applied to create a ceramic capacitive pressure microsensor with screen-printed diaphragm. The capacitive sensor design was realized. Diaphragm deflection under applied pressure was mathematically simulated. Capacitive sensors were fabricated utilizing sacrificial layer thicknesses of 12 and 22 μm . The cavity creation was again verified through microsectioning techniques. The 12 and 22 μm SLT devices had average capacitance values of 8.1238 pF and 5.9647 pF respectively. Room temperature pressure characterization was performed over the pressure range of 0 to 60 psig. The 12 and 22 μm SLT devices had average pressure sensitivities of 11.5 fF/psi and 22.0 fF/psi respectively. A sensor that had not been etched, thus no cavity, was pressure characterized utilizing the same interconnection

leads and testing apparatus. The unetched device capacitance did not change significantly with pressure. This characterization showed that the capacitance change of the etched sensors was truly a result of the diaphragm deflection under pressure. The capacitance change with pressure tracked well with the mathematically simulated diaphragm deflection. Again to evaluate the device suitability for high temperature applications, pressure versus capacitance testing at elevated temperatures of 100 °C, 200 °C, and 300 °C was performed on the 12 µm SLT devices. The 12 µm SLT device showed an average sensitivity of 9.2 fF/psi over the temperature and pressure ranges of 21 °C to 300 °C and 0 to 50 psig respectively. The effect of temperature alone on the pressure sensor was also analyzed. The 12 µm sacrificial layer device showed an average temperature coefficient of capacitance (TCC) of 68.3 ppm/°C over the temperature range of 25° C to 125° C and 96.9 ppm/°C over the temperature range of 15 °C to 300 °C. In order to discern if the sensor TCC characteristic was due to the dielectric material properties or the microstructure itself, devices that were not etched and thus no cavity, were analyzed for TCC. The TCC of the unetched devices were in close agreement with the etched sensors. This close agreement demonstrates that the sensor's TCC characteristic is primarily due to the dielectric material properties and is not the result of a physical cavity microstructure change with temperature. This temperature sensitivity is very low and another characteristic that verifies the fabricated devices suitability as a discrete high temperature pressure microsensor. With these results, the first target microsensor application of this research has been realized - discrete ceramic microsensors for high temperature applications.

After the successful realization of the discrete capacitive pressure sensor, work was undertaken to develop a second type of discrete thick film sensor – a PZR sensor. Development of a second type of thick film sensor displays the flexibility of the novel microstructure created in this research. Discrete thick film PZR sensors on a screen-printed diaphragm were designed and fabricated. The PZR sensors had a nominal resistance value of 3,585.67 ohms compared against the theoretical calculation of 3,533.21 ohms. The PZR sensors were characterized for applied stress versus resistance using a 3-point bending test. The device sensitivity calculated to $-877 \text{ m}\Omega/\text{N}$ over the applied force range of 0 to 2.94 Newtons. Again, as a stress sensor, placing the PZR sensor on the diaphragm would be vital in applications where the anticipated stresses are so high that decoupling the sensor slightly from the substrate is necessary. The PZR sensors were also pressure characterized. Since the PZR device is sensitive to stress, it could only be used in pressure sensing applications where there were no package stresses or in conjunction with a PZR stress sensor deposited directly on the substrate. In this latter situation, the portion of the resistance change due to stress could be compensated for. The device sensitivity was $-53.6 \text{ m}\Omega/\text{psi}$ and was fairly linear over the pressure range of 0 to 60 psig. Lastly, the effect of temperature alone on the PZR sensor was measured. The temperature coefficient of resistance (TCR) of the sensors over the temperature range of 25°C to 300°C was $-96.7 \text{ ppm}/^\circ\text{C}$ which met the data sheet specification for the thick film PZR material. A sensor that had not been etched was also characterized to demonstrate the sensor TCR was due to the PZR material itself and not a result of a cavity microstructure change with temperature. The measured TCR for the unetched sensor was $-112.4 \text{ ppm}/^\circ\text{C}$ over this same temperature range which is in very

close agreement with the measured sensor TCR. After a second sensing mechanism type was realized, an integrated substrate with both sensors was fabricated to show that substrates could be made which incorporated imbedded sensors with different sensing mechanisms. The integrated substrate was realized. The PZR sensors on the integrated substrate were stress characterized over the range of 0 to 3 Newtons and they showed a sensitivity of $-860 \text{ m}\Omega/\text{N}$ which was in very good agreement with the stress sensitivity of the discrete PZR sensors. The last effort of this research was to fabricate a smart ceramic packaging module prototype that would indicate loss of package hermeticity. A discrete capacitive pressure sensor was surface mounted onto the thick film interconnection substrate of a microelectronic module. The module was exposed to decreasing pressures of 5 to 0 psig to simulate loss of package hermeticity. The pressure versus capacitance data was very linear with a measured sensitivity of -27 fF/psi over the range of 5 psig to 0 psig. With these results, the second target microsensor application of this research has been enabled – imbedded sensors for smart ceramic packaging.

6.2 Research Contributions

The significant contributions of this work on high temperature discrete ceramic microsensors and smart ceramic packaging research fall into four categories: material, fabrication technique, device, and packaging.

The first impact was the development of thick film on alumina ceramic as an alternate material to silicon for harsh environment sensor applications. Alumina has superior material properties to silicon in many areas. Much of the previous research in ceramic pressure microsensors has been focused on LTCC technology. Thick film on alumina is superior to LTCC in the properties of shrinkage, flexural strength, Young's Modulus, and

thermal conductivity. The primary advantage of thick film over LTCC is cavity depth and diaphragm thickness design flexibility. This capability permits sensor designs in applications where fixed cavity depths and diaphragm thicknesses do not meet the required sensitivities.

The second major impact of this work was the development of a novel fabrication method combining thick film and MEMS fabrication techniques. The use of a sacrificial thick film layer to create a sealed cavity microstructure is new work. This cavity showed excellent hermeticity after high temperature exposures.

The third impact of this work was the creation of discrete thick film ceramic capacitive and PZR microsensors on a screen-printed dielectric diaphragm that show excellent performance over high temperature environments. The capacitive devices have excellent hermeticity, pressure sensitivity, and very low temperature coefficient. The PZR devices showed good resistive response to stress and pressure changes. The PZR sensors also had low temperature coefficient but not quite as good as the capacitive microsensor.

Lastly, both types of sensors were integrated onto the same substrate. A smart ceramic packaging module prototype was fabricated. Pressure characterization of the prototype showed that the ceramic sensors could be utilized to monitor microelectronic module reliability failure mechanisms such as loss of package hermeticity. This demonstrated ability enables smart ceramic packaging.

6.3 Suggestions for Future Work

Several aspects of this work can be further investigated.

First, device structures with other sacrificial layer thicknesses and diaphragm thicknesses should be simulated and fabricated to discover the limitations of this technology.

Second, due to limitations of testing and interconnection capabilities, the capacitive pressure sensor was only tested up to 300 °C. By the nature of the ceramic thick film material system which fires at 850 °C, the device should have the capability to perform well beyond 300 °C. If testing and interconnection techniques could be further developed, the true temperature performance limitations of this device could be discovered.

Third, the PZR sensors were only tested at room temperature for stress and pressure sensitivity. Elevated temperature stress testing of the PZR sensors was not possible due to equipment limitations. Elevated pressure testing of the PZR sensors was not done due to an insufficient quantity of material and devices. Elevated temperature characterization of the PZR sensor would be necessary to determine the device suitability for high temperature applications.

Fourth, all of the measurements were made using a sophisticated laboratory equipment. For the devices realized in this work to be useful commercially, signal conditioning circuitry would be necessary and should be investigated.

Finally, the actual imbedding of thick film sensors in a microelectronics module interconnection substrate which incorporates signal conditioning and temperature compensation circuits as illustrated in Figure 5.1 is necessary.

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