

Improved SiC Leadless Pressure Sensors For High Temperature, Low and High Pressure Applications

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ABSTRACT

This paper reports on the fabrication, packaging, and testing of improved SiC piezoresistive pressure sensors operational up to 600°C in both low and high pressure ranges. Sensor fabrication was done using a combination of Deep Reactive Ion Etching (DRIE) and electrochemical etching. This paper also reports on the design and evaluation of sensors with optimized sensing diaphragms containing “bossed” areas. As compared to the previous non-bossed round diaphragms, the sensors reported herein demonstrate a significant improvement in sensor output, linearity and repeatability. The 1000 psi sensors had diaphragms of more than 60µm thickness, while the 25 psi range required significantly thinner diaphragms of less than 20µm thickness. As opposed to alternative devices, the sensors described herein had both the piezoresistors and diaphragms fabricated from SiC. The utilization of a SiC diaphragm, due to excellent mechanical properties of SiC at very high temperatures and due to SiC

chemical inertness, makes these sensors suitable for use in: 1) extremely high temperature applications and 2) in extremely harsh environments.

Introduction

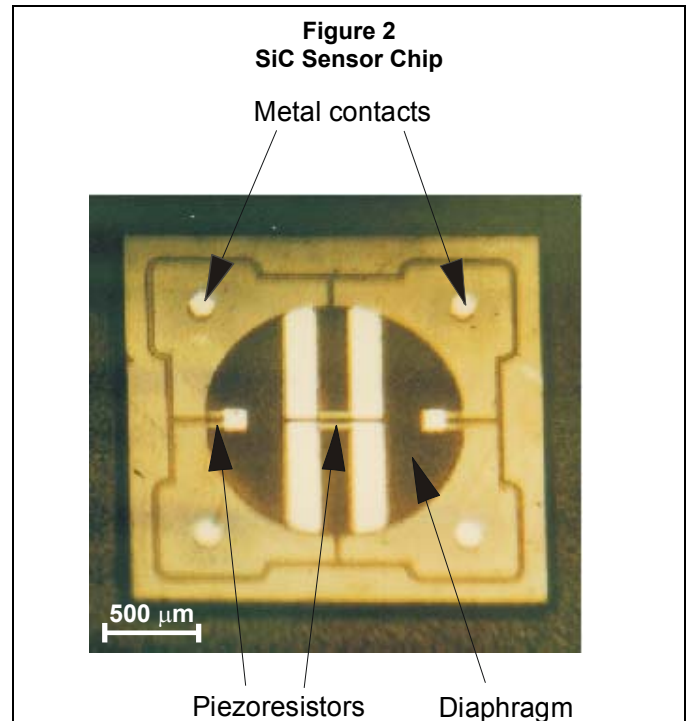
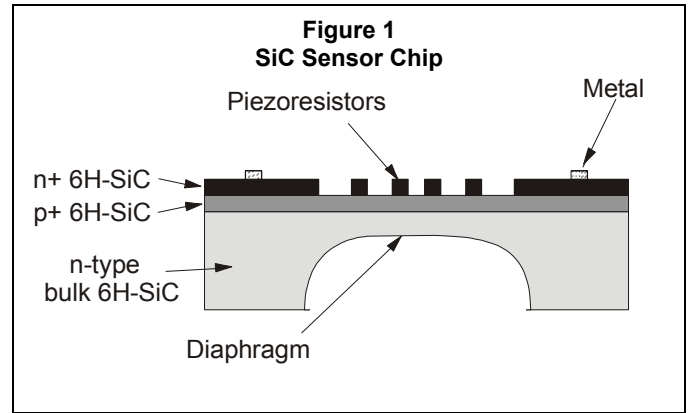
Increased performance requirements for pressure transducers for many military and commercial engines demand sensing capabilities at high temperatures. The pressure environments to be measured in these applications require sensing typically from 25 psi up to few thousand psi. To meet the high temperature requirements, silicon carbide (SiC) was selected as a semiconductor material to be used in fabrication of the sensor chip. SiC material, because of its wide bandgap (3eV), high breakdown electric field ($2.5 \times 10^6 \text{Vcm}^{-1}$) and large piezoresistive gage factors (10-20) exhibits excellent thermal, mechanical and electrical characteristics as a sensing material (1,2,3).

A number of groups working on high temperature pressure sensors have reported devices having 3C-SiC piezoresistors on silicon diaphragms.

Zappe et al. (4) reported sensors with 145-psi range, operational up to 300°C, with piezoresistors fabricated from 3C-SiC films grown on silicon-on-insulator (SOI) wafers. Wu et al. (5) reported 3C-SiC/SiO₂/Si sensors with 70-psi range, operational up to 385°C, fabricated using wafer bonding. In all of these approaches, however, the sensing diaphragm is fabricated from silicon with silicon becoming the limiting factor. The use of SiC for sensing elements only is thus not productive. Sensors produced using an all silicon (SOI) approach with silicon used for fabricating both the piezoresistors and the diaphragms have the same ultimate temperature limitation, but with much better overall performance characteristics (7,8,9,10). In order to fully utilize the benefits of SiC material, both the piezoresistive sensing elements and the sensing diaphragm should be fabricated from SiC. This paper reports on the fabrication and evaluation of both low and high pressure SiC piezoresistive pressure sensors operational up to 600°C.

Fabrication of SiC Pressure Sensors

Pressure sensors for high-pressure applications (~1000 psi range) capable of operating up to 600°C have been previously reported (11, 12, 13). The cross-sectional drawing and a photograph of a typical SiC pressure sensor chip are depicted in Figs. 1,2. The diaphragm for the 1000 psi sensor is relatively thick (~60 μm), while the diaphragm for the 25 psi pressure sensor is micromachined to be significantly thinner.



Fabrication of thin 6H-SiC diaphragms is very difficult: 1) because of challenging control of SiC etch depth, 2) because of presence of 6H-SiC micropipe defects (14) that become more pronounced the thinner the diaphragm becomes, and 3) because of an increased criticality of the placement of piezoresistors on the diaphragm.

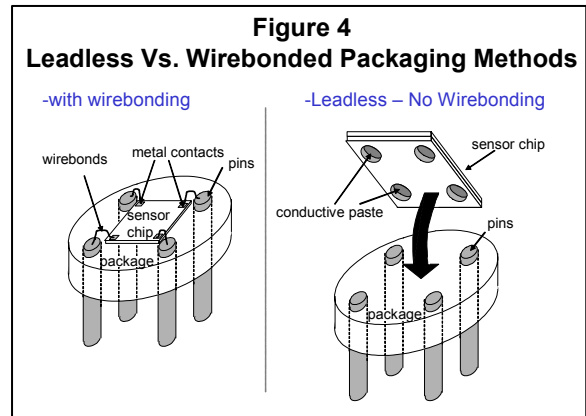
The fabricated 25psi sensors are similar in structure and geometric layout to the high-pressure counterparts. However, a diaphragm thickness of less than 20μm-

is required as compared to $\sim 60\mu\text{m}$ -thick diaphragms for the 1000psi sensors. The diaphragm fabrication with improved control of SiC etching parameters was done using a combination of Deep Reactive Ion Etching (DRIE) and electrochemical etching. The DRIE etching enabled a high aspect ratio in the formation of the walls in the diaphragm cavity, and also improved uniformity across the sensing diaphragm, while the electrochemical etching added to the control of diaphragm shaping, and enabled smoothing of the sharp edges. Sharp edges act as potential stress raisers and lead to premature fracture of the diaphragm. A photograph of the micromachined diaphragm is depicted in Fig. 3.



The micropipe defects, which are inherent to currently available SiC wafers, and which are detrimental to sensor performance, were closed on the wafer level using a previously developed oxidation approach (15). This approach was modified for thinner diaphragms.

The placement of piezoresistors and the uniformity of the diaphragm in the region where the piezoresistors are placed is very critical for low pressure sensing. Finite element modeling is performed to better understand and optimize the low-pressure sensor design. Critical care is taken to assure proper placement of the piezoresistors. The rest of the processes are kept unchanged from those implemented in the fabrication of the high-pressure sensors.

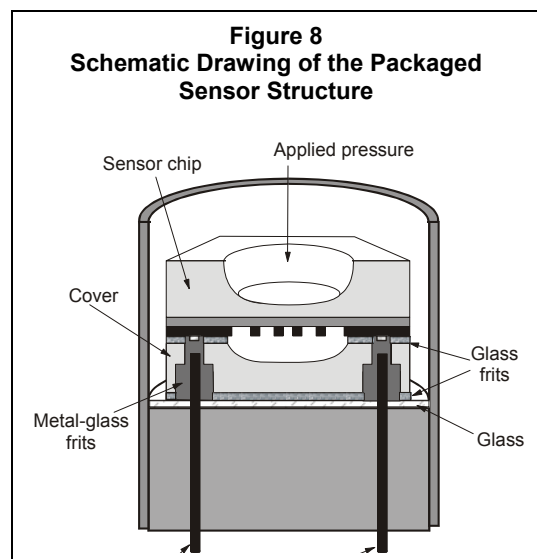
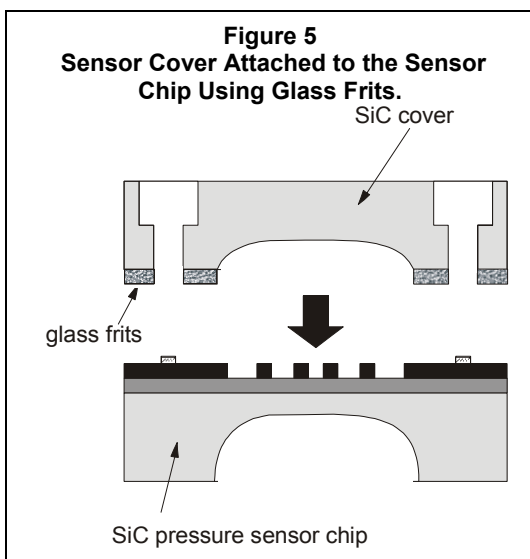
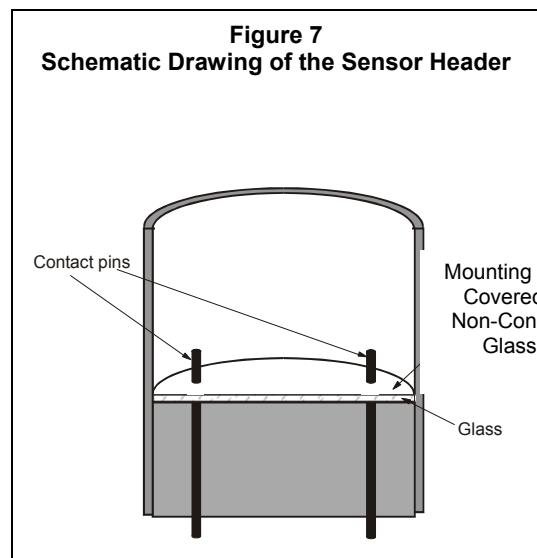
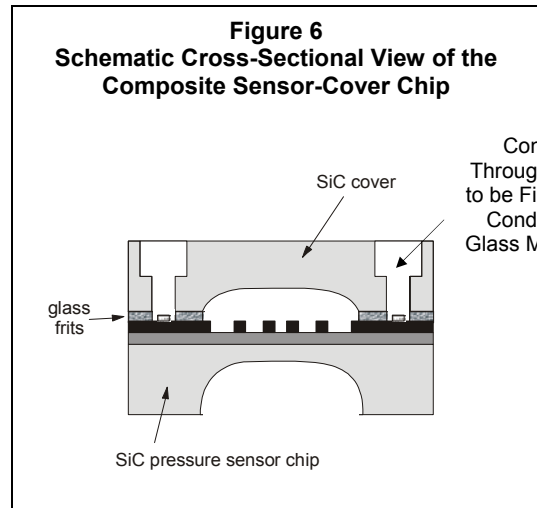


Leadless Packaging of SiC Pressure Sensors

The leadless packaging technique avoids the use of wirebonds (Fig. 4) which is considered to be one of the failure modes at high temperatures.

Electrical contacts between metallized pads of the sensor chip and pins of the sensor header are made using an electrically conductive metal-glass frits mixture. The requisite package components are a sensor cover and a sensor header. The sensor chip, cover, and header are bonded using electrically nonconductive glass frits. The packaging process steps are presented in Figs. 5-8. The SiC sensor cover was fabricated using DRIE and electromechanical etching. It has a cavity for diaphragm deflection and four

through holes aligned with the metallized pads of the sensor chip for electrical contacts. The through holes were micromachined using Deep Reactive Ion Etching on both sides of a SiC wafer following a process described elsewhere [16]. Subsequently, the cavity was etched on one side of the wafer using electromechanical etching [17]. After sensor chips and covers were batch fabricated, they were bonded together using specifically selected glass frits (Fig. 5). A schematic cross-sectional drawing of the sensor chip with cover is shown in Fig. 6. The electrically conductive metal-glass frits mixture was dispensed in the through holes of the cover, and the nonconductive glass frits were dispensed over the mounting surface of the header (Fig. 7). The composite SiC sensor-cover chip was flipped over and placed inside the header. The glass frits used for die attachment as well as the metal-glass frits mixture for electrical contacts were simultaneously fired at 650° C. The structure of the resulting packaged sensor is schematically shown in Fig. 8.



Sensor Performance Characteristics

The fabricated SiC low and high sensors were evaluated up to 600°C. The data (Fig. 9) were consistent with previously reported non-monotonic resistance change with temperature. This continues to pose a big challenge for temperature compensation of such SiC sensors. Additionally, although the performance characteristics such as sensitivity, linearity and hysteresis were improved, there is still an issue with a large thermal set (10mv) being observed in all SiC sensors after exposure to 600°C.

Figure 9
Leadless SiC Sensor

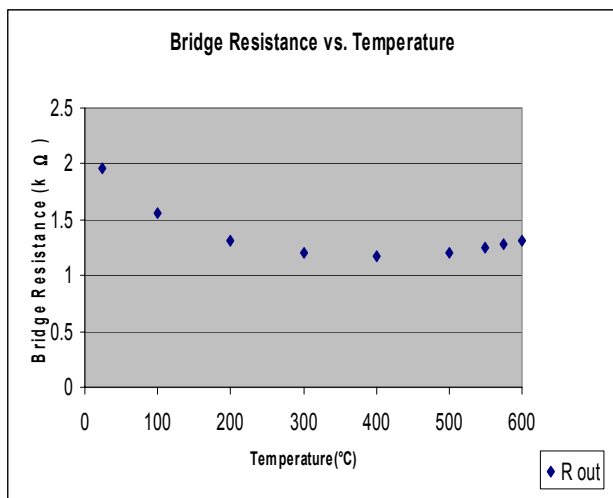
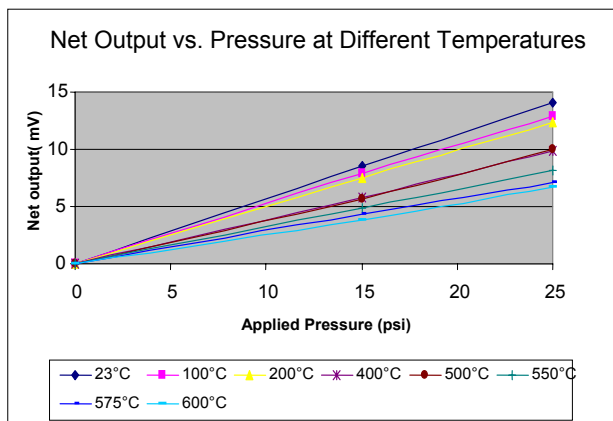


Figure 10
Leadless SiC Sensor



Conclusion

The utilization of SiC diaphragms and SiC sensing elements truly enables the SiC sensors to be suitable for high temperature operability (due to utilization of all the excellent mechanical, electrical, and chemical properties of SiC at very high temperatures).

Fabrication, packaging, and testing of low and high pressure SiC piezoresistive pressure sensors ranging from 25 psi up to 1000 psi operational up to 600°C was demonstrated. The behavior of these sensors was consistent with the previously reported performance characteristics of SiC sensors.

Work on optimizing the SiC sensor design and processing is presently underway.

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Acknowledgments

We would like to acknowledge support from the Higher Operating Temperature Propulsion Components Project of the NASA Glenn Research Center.