Single Crystal SiC Capacitive Pressure Sensor at 400 °C

Jiangang Du, Darrin J. Young, Christian A. Zorman, and Wen H. Ko

EECS Department, Case Western Reserve University
Cleveland, Ohio, USA 44106

Abstract

Single crystal 3C-SiC capacitive pressure sensors are proposed for high-temperature sensing applications. The prototype device consists of an edge-clamped circular SiC diaphragm with a radius of 400 μm and a thickness of 0.5 μm suspended over a 2 μm sealed cavity on a silicon substrate. The fabricated sensor demonstrates a high-temperature sensing capability up to 400 °C, limited by the test setup. At 400 °C, the device achieves a linear characteristic response between 1100 Torr and 1760 Torr with a sensitivity of 7.7 fF/Torr, a linearity of 2.1 %, a hysterisis of 3.7%, and a sensing resolution of 9.1 Torr (12 mbar).

Introduction

High-temperature pressure sensors are highly critical for industrial, automotive, and aerospace sensing applications. Typical temperatures for these applications range from 200 °C to 600 °C. Silicon structures suffer from severe mechanical performance degradation above 500 °C and thus are inadequate for building reliable high-temperature sensors. SiC material is attractive for high temperature applications because of its mechanical robustness, chemical inertness, and electrical stability at elevated temperatures and is expected to perform reliably well above 500 °C [1]. Existing high-temperature pressure sensors are implemented using SiC-based piezoresistive devices and have demonstrated sensing capabilities around 350 °C [2, 3]. Piezoresistive sensors, however, exhibit a strong temperature dependence and suffer from severe contact resistance variations at elevated temperatures, substantially degrading the sensor performance. Capacitive pressure sensors are attractive for high-temperature applications because the device performance is tolerant of contact resistance variations and wireless sensing schemes can be readily realized [4, 5]. Furthermore, capacitive devices can achieve a high sensitivity, low turn-on temperature drift, and a minimum dependence on side stress and other environmental variations. In this paper, a single crystal 3C-SiC capacitive pressure sensor is presented. The prototype device demonstrates a sensing capability up to 400 °C, the highest temperature performance of semiconductor capacitive pressure sensors to date. The achieved performance is suitable for various high-temperature sensing applications.

SiC Capacitive Pressure Sensor

Figure 1 presents a simplified cross-sectional view of the proposed capacitive pressure sensor. The device consists of an edge-clamped circular 3C-SiC diaphragm suspended over a sealed cavity on a silicon substrate. The diaphragm deflects toward the substrate under an increasing external pressure, thus increasing the device capacitance value.

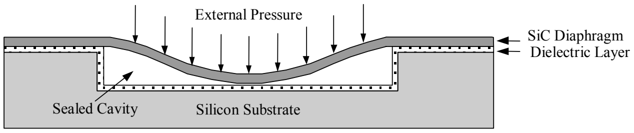

Figure 1. SiC Pressure Sensor Cross-Sectional View

Once the diaphragm touches the substrate at a designed touch point pressure, the sensor capacitance increases linearly with the pressure due to the linearly increasing touched area [6]. Figure 2 illustrates a typical device characteristic response between the sensor capacitance value and applied pressure.

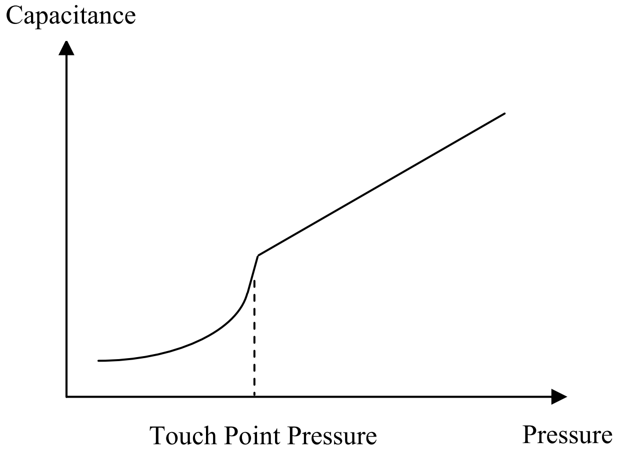

Figure 2. Pressure Sensor Characteristic Response

The linear behavior is desirable for various sensing applications. Single crystal 3C-SiC material is chosen for the bending diaphragm because it can be readily grown over a 4” silicon wafer surface with a controlled quality [7], thus ensuring reliable performance at elevated temperatures. The diaphragm thickness and radius, cavity depth, and dielectric layer thickness can be designed to obtain various pressure ranges, sensitivities, and sensor capacitance values [6]. Thus, sensors achieving a wide range of performance specifications can be fabricated from a set of masks by properly choosing the device vertical dimensions, an attractive advantage of the proposed sensor architecture.

Fabrication Process

Figure 3 presents the fabrication process flow for the prototype sensor. A 4-inch N-type <100> silicon wafer is etched by a reactive ion etch (RIE) process to form a 2 μm recess followed by depositing 2500 Å phosphorus silicate glass (PSG) as an insulation layer, as shown in Figure 3(a).

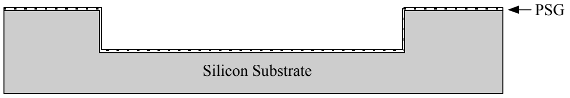

Figure 3(a) Recession Formation

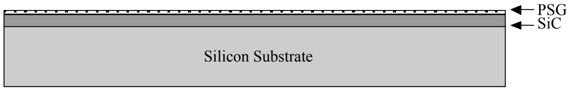

Figure 3(b) 3C-SiC and PSG Deposition

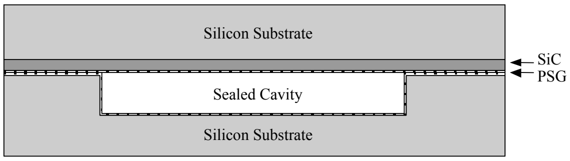

Figure 3(c) Wafer Bonding

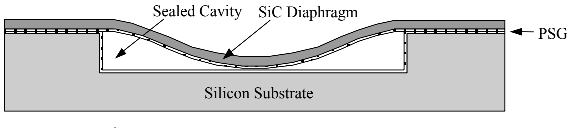

Figure 3(d) Diaphragm Formation

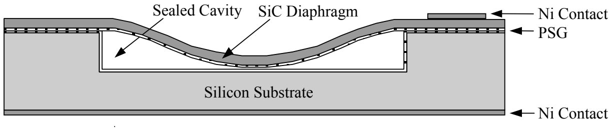

Figure 3(e) Contact Metallization

Figure 3. Sensor Fabrication Process Flow

Next, a 0.5 μm single crystal 3C-SiC is grown on the surface of another 4-inch N-type <100> silicon wafer by using an APCVD technique [7]. The film growth process consists of an in-situ cleaning of the silicon wafer surface in H_2 at 1000°C, followed by carbonization of the silicon surface using C_3H_8 and H_2 at 1280°C and then by film growth using SiH_4, C_3H_8 and H_2 also at 1280°C with a growth rate of approximately 1 μm per hour. The resulting 3C-SiC thin film exhibits a resistivity of approximately 0.5 Ω·cm and a tensile stress of 175 MPa. The SiC surface is then polished through a chemical mechanical polishing (CMP) step to minimize surface defects and uneven thickness, an important step for a successful subsequent wafer bonding. A 2500 Å PSG film is then deposited on the SiC surface, as shown in Figure 3(b). This PSG layer is critical for the wafer bonding because of the roughness of the SiC surface. The two wafers are annealed at 1000 ^{o}C under atmospheric pressure for an hour followed by a minor CMP process to achieve a smooth surface. The wafers are then thoroughly cleaned in a reverse RCA process to obtain hydrophilic surfaces and are bonded together under a pressure of approximately 400 Torr below atmosphere pressure, as shown in Figure 3(c). A high-temperature annealing step at 1000 ^{o}C for two hours is then performed to enhance the bonding quality. In the next step, the silicon substrate above the SiC layer is removed by TMAH to form a 0.5 μm thick SiC diaphragm. Due to the differential pressure, the diaphragm deflects toward the substrate and can touch the substrate depending on the structural compliance, as illustrated in Figure 3(d). A 5000 Å nickel layer is then sputtered on the both sides of the wafer with 100 Å titanium for adhesion enhancement and is patterned to form a high-temperature contact to the diaphragm [8], as depicted in Figure 3(e). The wafer is then diced, followed by gold wire bonding and applying high-temperature silver epoxy to establish the top and bottom electrode contacts, respectively, for device testing.

Experiment Results

Figure 4 shows a top view optical microscope photo of a fabricated SiC pressure sensor with a 400 μm-radius circular diaphragm. Newton rings are visible indicating the diaphragm bending due to the differential pressure across the diaphragm. Figure 5 presents an SEM micrograph of a partial device cross-sectional view, illustrating the 0.5 μm

SiC layer suspended over a 2 μm recess on the silicon substrate.

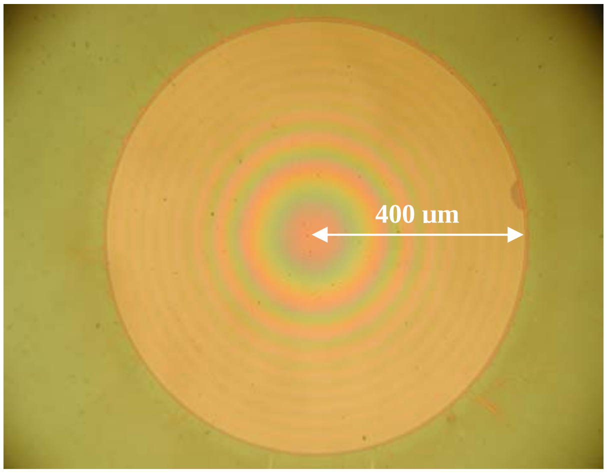

Figure 4. Top View of SiC Capacitive Pressure Sensor

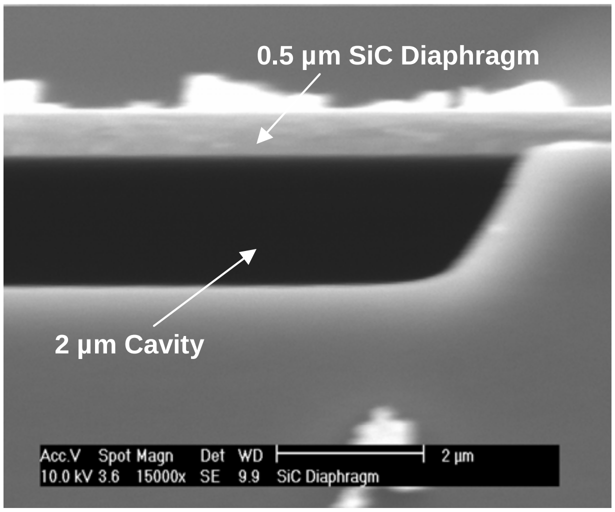

Figure 5. SEM of Pressure Sensor Cross-Sectional View

The fabricated sensors are annealed at 400 ^{o}C under atmospheric pressure for 48 hours to eliminate any device initial temperature dependence and drift prior to characterization. Figure 6 shows the device testing setup. The sensor is placed inside a sealed metal testing chamber with a temperature and pressure control. A thermal couple is positioned in close proximity to the sensor for measuring the device temperature. The device capacitance value is measured by a LCR meter as the chamber pressure is varied. Figure 7 presents the measured sensor capacitance change versus an externally applied pressure at 200 ^{o}C. The device exhibits a touch point pressure (P_T) of approximately 720 Torr with a total capacitance change of 13.5 pF over the pressure range from 295 Torr to 2500 Torr. The sensor achieves a linear characteristic response between 900 Torr and 1450 Torr with a sensitivity of 8.0 fF/Torr and enters a saturation region with a reduced sensitivity beyond 1500 Torr due to the device geometry.

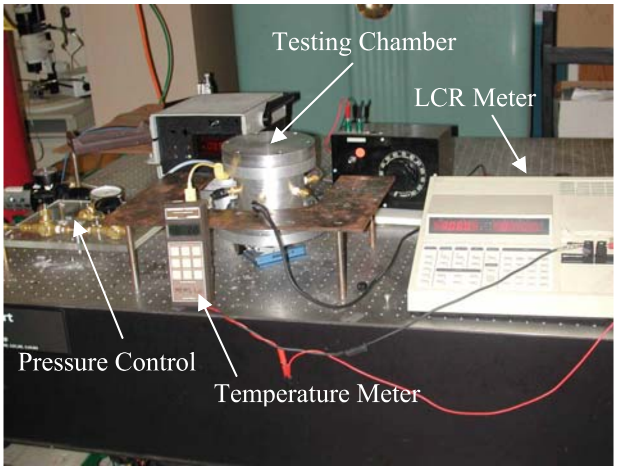

Figure 6. Testing Setup

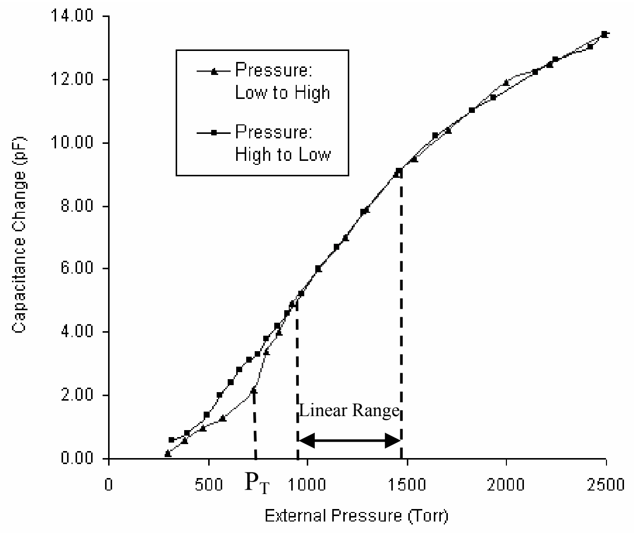

Figure 7. Sensor Characteristic Response at 200 ^{o}C

Various linear ranges and sensitivities can be obtained by properly choosing the diaphragm radius and cavity depth [6]. The device exhibits a linearity of 0.7 % and hysteresis of 0.5 % within the linear range. The high-temperature sensor performance has been demonstrated up to 400 ^{o}C as shown in Figure 8 and is limited by the current test setup. At 400 ^{o}C, the device exhibits an expected touch-mode behavior with a touch point pressure of approximately 1000 Torr and achieves a linear characteristic response between 1100 Torr and 1760 Torr with a sensitivity of 7.7 fF/Torr, a linearity of 2.1 %, and a hysteris of 3.7%. The measurement results indicate that the prototype capacitive pressure sensor is tolerant of contact resistance variations at elevated temperatures. However, the device exhibits separate characteristic curves at different temperatures, as shown in Figure 8, due to the trapped air inside the cavity during the wafer bonding. The trapped air causes the sensor touch point pressure to increase near linearly with the temperature, thus resulting in separate characteristic curves. This temperature dependent effect can be substantially minimized by eliminating the trapped air inside the cavity by wafer bonding in a vacuum.

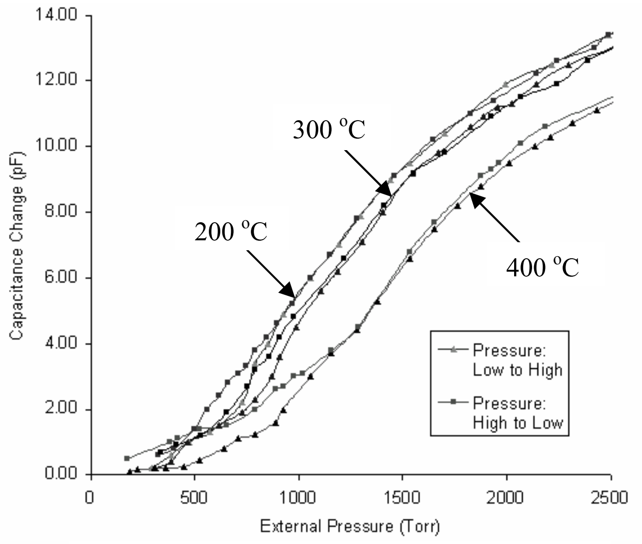

Figure 8. High-Temperature Sensor Response

Figure 9 presents the sensor capacitance measurement versus time as the temperature rising toward 400 °C.

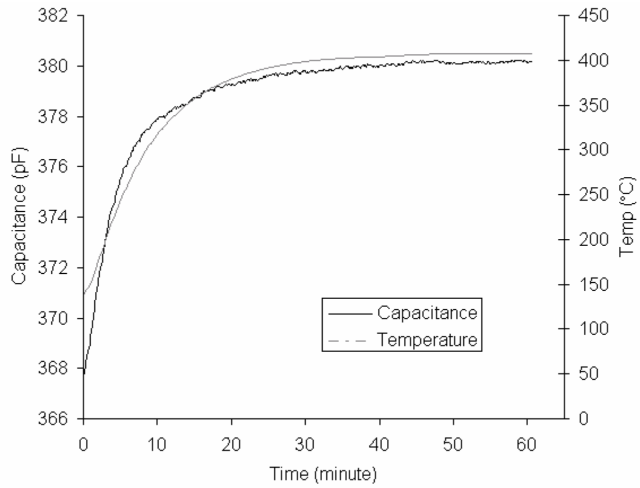

Figure 9. Sensor Capacitance Measurement at 400 °C

After the temperature stabilizes, the measured capacitance value exhibits a random fluctuation of approximately 70 fF, thus corresponding to a sensing resolution of 9.1 Torr (12 mbar). The demonstrated prototype sensor performance is adequate for various high-temperature sensing applications.

Conclusion

SiC material is critical for high-temperature environment sensing applications. The proposed capacitive pressure sensors employing single crystal 3C-SiC diaphragms have demonstrated sensing capabilities up to 400 °C. The fabricated devices are tolerant of high-temperature contact resistance variations. The exhibited device temperature dependence can be substantially minimized through wafer bonding in a vacuum.

Acknowledgements

This work is partially supported by NASA under Glennan Microsystem Initiative. All fabrication steps have been performed in the Microfabrication Laboratory at Case Western Reserve University.

References

[1] M. Mehregany, C. A. Zorman, N. Rajan, C. H. Wu, "Silicon Carbide MEMS for Harsh Environments," *Proceeding of the IEEE*, Vol. 86, No. 8, pp. 1594-1610, 1998.

[2] R. S. Okojie, A. A. Ned, A. D. Kurtz, and W. N. Carr, "α(6H)-SiC Pressure Sensors at 350 °C," *IEDM*, pp. 525-528, 1996.

[3] C. H. Wu, S. Stefanescu, H. I. Kuo, C. A. Zorman, and M. Mehregany, "Fabrication and Testing of Single Crystal 3C-SiC Piezoresistive Pressure Sensors," *Transducers*, pp. 514-517, 2001.

[4] M. Suster, W. H. Ko, and D. J. Young, "Optically-Powered Wireless Transmitter for High-Temperature MEMS Sensing and Communication," *Transducers*, pp. 1703-1706, 2003.

[5] M. A. Fonseca, J. M. English, M. von Arx, and M. G. Allen, "Wireless Micromachined Ceramic Pressure Sensor for High-Temperature Applications," *IEEE Journal of Microelectromechanical Systems*, pp. 337-343. 2002.

[6] W. H. Ko and Q. Wang, "Touch mode capacitive pressure sensors," *Sensors and Actuators* 75 (1999), pp. 242-251.

[7] C. A. Zorman, A. J. Fleischman, A. S. Dewa, M. Mehregany, C. Jacob, S. Nishino, and P. Pirouz, "Epitaxial growth of 3C-SiC films on 4-inch diameter (100) silicon wafers by atmospheric-pressure chemical vapor deposition," *J. Appl. Phys.* , Vol. 78, No. 8, pp. 5136-5138, 1995.

[8] C. Jacob, P. Pirouz, H. I. Kuo, M. Mehregany, "High temperature ohmic contacts to 3C-silicon carbide films," *Solid-State Electron*, Vol. 42, No.12, Dec. 1998. pp. 2329-2334.