Thermal Hysteresis of MEMS Packaged Capacitive Pressure Sensor (CPS) Based 3C-SiC

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Abstract. Presented herein are the effects of thermal hysteresis analyses of the MEMS packaged capacitive pressure sensor (CPS). The MEMS CPS was employed on Si-on-3C-SiC wafer that was performed using the hot wall low-pressure chemical vapour deposition (LPCVD) reactors at the Queensland Micro and Nanotechnology Center (QMNC), Griffith University and fabricated using the bulk-micromachining process. The MEMS CPS was operated at an extreme temperature up to 500°C and high external pressure at 5.0 MPa. The thermal hysteresis phenomenon that causes the deflection, strain and stress on the 3C-SiC diaphragm spontaneously influence the MEMS CPS performances. The differences of temperature, hysteresis, and repeatability test were presented to demonstrate the functionality of the MEMS packaged CPS. As expected, the output hysteresis has a low hysteresis (less than 0.05%) which has the hardness greater than the traditional silicon. By utilizing this low hysteresis, it was revealed that the MEMS packaged CPS has high repeatability and stability of the sensor.

1. Introduction

In microelectromechanical system (MEMS) devices, good quality refers to the simultaneous performance by the achievable mechanical, thermal hysteresis and stability [1]. The measurement of mechanical sensors achieved an excellent and simultaneous performance depending on the achievable repeatability and thermal hysteresis. These parameters influenced by the change of the sensor output such as pressure, temperature cycles and time. Thermal hysteresis is a phenomenon observed in the behaviour of a temperature-dependent property of the MEMS devices [2]. The sensing element in MEMS sensor depends on the capacitance between the mechanically deformed diaphragm and...
underlying electrode. Hysteresis occurs when a sensing relies on the stressing of a diaphragm. The 
change of the sensor output due to different pressures, cyclic temperatures and time will affect the 
hysteresis and long term stability of the MEMS devices [3]. The most significant aspect of maintaining 
the performance of a sensor is the selection of the materials.

In this study, a single crystal silicon carbide (3C-SiC) was used due to its high thermal conductivity 
(5 W/cm·°C) and breakdown electrical field (4 × 10^6 V/cm) which indicate a great potential in the high 
power and electronic application temperature compared to silicon-based components as shown in Table 
1 [4]. A wide band-gap up to 2.3 eV has the capability to reduce the thermal management, high frequency 
and surge current capabilities and inherent radiation hardening for the MEMS applications. The wide 
band-gap in MEMS technology has the potential to reduce the size and weight of power generation and 
supply systems, increase power density and improve power efficiency [5].

| Material properties          | Silicon        | 3C-SiC         |
|------------------------------|----------------|----------------|
| Young’s modulus (GPa)        | 1.69           | 4.70           |
| Poisson ratio (ν)            | 0.30           | 0.22           |
| Density (kg/µm³)             | 2.5 x 10^{15}  | 3.2 x 10^{15}  |
| TCE Integral Form (1/K)      | 2.5 x 10^{-6}  | 2.3 x 10^{-6}  |
| Thermal Conductivity (pW/µmK)| 1.48 x 10^{48} | 5.0 x 10^{48}  |
| Specific Heat (PJ/kgK)       | 7.12 x 10^{14} | 1.34 x 10^{15} |
| Dielectric constant          | 9.72           | 11.68          |

Based on the mechanical and physical properties of both materials 3C-SiC can be classified as the 
greatest available material for the mechanical sensors and other MEMS device applications. The major 
advantages include the ability of the materials to withstand mechanical and thermal hysteresis, high 
strength, high sensitivity to stress and excellent long-term mechanical stability.

2. Theory

Theory of repeatability

Repeatability is a measurement precision under repeatability conditions including the same 
measurement procedure, operator, measuring system, operating conditions and location. It also 
replicates measurements over a short period of time. Repeatability is the potential of the sensor to 
respond in an identical way with the same output to the same input signal given the same conditions. It 
is commonly expressed as standard deviation, s of the values obtained from repeated measurements. Repeatability refers to the ability of the sensor to produce the same output with sequential applications of the same pressure [6].

Theory of hysteresis error

The measurements were conducted to determine the specification tests including the reliability 
and thermal hysteresis error. The hysteresis $k$ is calculated as Equation (1) where $C_{down}$ and $C_{up}$ are 
the capacitive output signals measured on the decreasing pressure curve and increasing pressure curve 
respectively [7].

$$k = \frac{C_{down}(p) - C_{up}(p)}{C_{up}(p)} \times 100\%$$ (1)
3. Methodology

3.1. Packaging and calibration

The sensor contains three parts of fabrication process: (i) fabrication of 3C-SiC diaphragm; (ii) fabrication of silicon substrate and (iii) bonding process between diaphragm and substrate. The assembly and packaging MEMS packaged CPS is as referred in our previous research [8]. The experimental test is operated as shown in Fig.1 and schematic in Fig. 2. The setup includes six main components including a nitrogen gas cylinder, pressure regulator, reference pressure gauge, temperature controller, extreme heating tape and LCR meter. The interconnecting tubing is made up from the SS materials. The high-pressure nitrogen gas up to 5 MPa was monitored to the required pressure by using a pressure regulator and gauge. The four-wire measurement was used to quantify pressure responses to determine the performance of MEMS packaged CPS such as hysteresis, sensitivity, linearity, and reliability.

![Figure 1 Calibration and experimental set-up for the MEMS packaged CPS](image1.jpg)

![Figure 2 The schematic of operational MEMS CPS](image2.jpg)
4. Results and discussion

Fig. 3 shows the COMSOL 4.2 simulation results which indicate the maximum von Mises effects on the diaphragm when the pressure is from 0 to 5 MPa. The maximum von Mises stress results versus the pressure and operating temperature distribution on the MEMS packaged CPS diaphragm as the applied pressure and temperature were due to the effect of friction heat and elastic deformation on the surface diaphragm. It was found that as the pressure and operating temperature increased, the maximum von Mises stress linearly increased for 3C-SiC, while nonlinearly increased for Si. The main reason can be that the von Mises stress distribution on the diaphragm increases linearity which has proven that the 3C-SiC materials can generate some amount of thermal energy.

The results also show the effect of von Mises stress which appeared on the surface diaphragm at the point of loading pressure as shown in Fig. 4. For 3C-SiC, the maximum von Mises stress with an applied pressure of 10 MPa and temperature of 1000°C increased linearly with the thickness of the diaphragm which were 1.0 µm, 1.6 µm and 2.2 µm with a higher value of von Mises stress which were 36.36 MPa, 60.51 MPa and 125.48 MPa, respectively. It was demonstrated that the linear analysis indicates a uniform state of stress proportional to the strain function as well as high sensitivity for a MEMS packaged CPS equipped with the thickness of the diaphragm.

It was revealed that the 3C-SiC material can survive in resisting a very high pressure and extremely high temperatures without fracture. For the Si materials, the results presented more realistic nonlinear responses to an applied pressure and operating temperature which explained the unconditional stability of the materials with respect to the strain increments. It is possible that the high stresses monitored at these stress concentration areas were due to the thermal stresses caused by thermal expansion and contraction of the materials produced by thermal gradient. The major thermal stress-induced can cause failure of diaphragm materials that affects the nonlinear behaviour exhibited under the prestressing and thermal effects.
The MEMS packaged CPS is subjected to a varying pressure from 0 – 5.0 MPa and different room temperatures at 27°C, 300°C and 500°C as shown in Fig. 5. To evaluate thermal hysteresis the signal was recorded both for increasing and decreasing pressure at differential pressures. By compiling the data, for room temperature, at 0 MPa, the capacitance was measured to be 14.015 pF and at 5.0 MPa it increased to 19.986 pF. For 300°C and 500°C, at 0 MPa, the capacitance was measured to be 12.903 pF and 11.591 pF, respectively. The thermal hysteresis error calculated from Equation (1) was 0.0465%.

Three different regions of operation were identified. The sensor operated in normal mode (non-touch mode) below 1.0 MPa and a transition region between 1.2 to 4.6 MPa. In the touch mode operation, the majority of the capacitance was due to the contact area and the increase in contact area was nearly linear with pressure with the characteristic response of 0.878%. Thus, the capacitance increase was nearly linear in this region. Furthermore, the sensitivity was higher than in the non-touch mode operation. The results were also tested for three repeatability tests and found the same behaviour in Fig. 6. This approach gave flexibility of the MEMS packaged CPS up to 500°C and pressure up to
5.0 MPa with 0.158%. Thus, it can be concluded that the MEMS packaged CPS provides the accurate, repeatable and acceptable ability for commercial purposes in the MEMS technology sensor for harsh environment.

Figure 6 The three tested groups of pressure-capacitance at temperature of 27°C, 300°C and 500°C

5. Conclusion

The high-temperature analysis of the MEMS packaged CPS based 3C-SiC was successfully verified in a differential temperature which provided evidence that the MEMS packaged CPS based 3C-SiC can operate up to 500°C. In addition, the pressure sensing capabilities of the MEMS packaged CPS exceeded 5.0 MPa were successfully demonstrated in a high-temperature-pressure experimental testing. The MEMS packaged CPS achieved a linear characteristic response and the repeatability and thermal hysteresis errors of 0.878%, 0.158 %, and 0.0465 %, respectively.

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