HIGH RESOLUTION SILICON CARBIDE RESONANT STRAIN GAUGE AT 600 ºC

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ABSTRACT

In this paper, we present the viability of silicon carbide (SiC) MEMS strain gauge for applications in high temperature and harsh conditions, validated by experimental results. Silicon carbide is a MEMS material well-suited for harsh environments due to its excellent mechanical properties, as well as thermal and chemical stability at high temperature and corrosive environments. The work presented here is focused on fabrication and testing of a high resolution SiC strain gauge. The resolution of the strain gauge is 0.045 με at a 10 kHz bandwidth measured using a previously developed square wave oscillator circuit. We report the 600ºC operation of this strain gauge in atmospheric conditions.

Keywords: Silicon carbide (SiC), MEMS, DETF, resonant strain gauge, harsh environment

1. INTRODUCTION

Sensors capable of working at very high temperatures, intense vibrations, and/or corrosive media are desired for component monitoring in boiler plants, combustion engines or gas turbines. Silicon-based sensors are not suitable for these harsh environments because of the degradation of its material properties at temperatures above 500ºC [1] and the breakdown of silicon (Si) electronics beyond 250ºC. Silicon carbide (SiC) has long been recognized as an alternative to Si for harsh environment applications. SiC exhibits excellent mechanical properties, chemical inertness, radiation resistance, high thermal conductivity, and wide bandgap [2]. Moreover, single and polycrystalline SiC can be grown and deposited on large area substrates and are compatible with batch-fabrication processes, which has lowered the cost of SiC MEMS and electronics.

In this work, a high resolution SiC MEMS strain gauge is developed for harsh environment applications. A strain gauge is a device used to measure small deformation of an object. It is typically bonded to the surface of a solid body to measure the minute dimensional changes due to compression or tension. For high precision measurements, double-ended tuning fork (DETF) resonant sensors are an excellent choice because they exhibit high strain sensitivity for a given gauge length. Silicon comb-drive DETF resonators have been successfully demonstrated in strain sensors which achieve extremely high strain resolution [3], as well as in accelerometer [4] and gyroscope [5] applications.

This paper reports the latest results of a poly-SiC balanced-mass double-ended tuning fork (BDETF) resonant strain gauge. The fabricated sensors resonate in air with frequencies ranging from 204-207 kHz and achieve a resolution of 0.045 με at a 10 kHz bandwidth. This work also shows the sensor operation at 600ºC, which enables progress towards development of an integrated harsh environment strain sensor module. The design, fabrication, and testing of the sensor are presented in the following sections.

2. DEVICE STRUCTURE & FABRICATION

The resonator structure and principle of operation has been presented in detail by Azevedo et al. [6]. In order to achieve higher operation temperature and reduce the effect of thermal cycling, we modified the previously reported fabrication process flow. There were two key changes we made to the process. First, an all-SiC fabrication process yields the lowest mismatch in thermal coefficient of expansion (TCE), ensuring reliable operation. Therefore, the poly-Si routing layer was replaced with low-pressure chemical vapor deposition (LPCVD) poly-SiC. Secondly, the low-temperature oxide (LTO) insulation layer is seen as a potential failure point under high thermal cycling as well as in a corrosive media. Therefore, the LTO was replaced with a thick LPCVD low-stress silicon nitride (LSN) in the new fabrication process. LSN is more corrosion-resistant than oxide, and has been used as protective coating by the IC industry and as an etch mask for KOH etching [7]. Moreover, LSN has higher thermal conductivity than oxide and its TCE is significantly closer to SiC than oxide. The final structural layers of the fabricated device are shown in Figure 1. These changes are expected to reduce the thermal mismatch between layers and improve the oxidation resistance, providing a strain sensor capable of working at 600ºC. The material properties of different thin films are summarized in Table 1 [8, 9]. The aforementioned changes will also accelerate the future transition of this device from Si substrate to SiC substrate, creating an all-SiC sensor.

![Figure 1: Layer structure of the resonant strain gauge](image-url)
The four-mask fabrication process is detailed as follows. We begin with a 100-mm diameter n-type (100) silicon wafer and deposit LSN (1.3 μm) by LPCVD. The first mask is used to pattern the thick LSN layer using Lam Autoetcher 590 to provide electrical contact to the substrate (Figure 2a). Subsequently, in-situ nitrogen-doped poly-SiC (300nm) was deposited by LPCVD using an optimized recipe for achieving low film residual stress (~300MPa tensile) and low resistivity (~0.025Ω·cm) [10]. The poly-SiC layer was patterned to form the electrical routing layer (Figure 2b). Then, a thick LPCVD LTO (2μm) is deposited and annealed at 950°C for 1 hour to serve as the sacrificial release layer (Figure 2c). After anchors and electrical contact points were patterned on the LTO using Lam Autoetcher 590, thick poly-SiC (7 μm) was deposited by LPCVD, and patterned using LTO as the etch mask to form the resonator structure (Figure 2f) [6].

Patterning of all the poly-SiC films in the fabrication process was performed with plasma etching in a commercial LAM TCP 9400 system, using etch vapor mixture of HBr (125 sccm) and Cl₂ (75 sccm). The TCP forward and bias powers used are 300W and 150W respectively, while the chamber pressure is kept at 12 mtorr for optimized etch selectivity and sufficient etch rate [11].

Thicknesses of deposited thin films were measured using Nanospec 4000 AFT Spectrophotometer and confirmed by cross-sectional scanning electron microscope (SEM). Resistivity values were obtained using Tencor RS35C 4-Point Probe. Finally, the etch mask and sacrificial oxide were removed in vapor hydrofluoric acid to release the resonator structure (Figure 2g). Figure 3 shows the optical micrograph of the fabricated device.

### Table 1: Material properties of different thin films

<table>
<thead>
<tr>
<th>Material</th>
<th>4H-SiC</th>
<th>Poly-SiC</th>
<th>Poly-Si</th>
<th>LSN</th>
<th>SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant</td>
<td>9.66</td>
<td>9.72</td>
<td>11.7</td>
<td>7.5</td>
<td>3.9</td>
</tr>
<tr>
<td>Dielectric strength (10⁶V/cm)</td>
<td>3.5</td>
<td>3</td>
<td>0.3</td>
<td>6.5</td>
<td>13</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>448</td>
<td>340</td>
<td>160</td>
<td>290</td>
<td>57</td>
</tr>
<tr>
<td>Thermal conductivity (W/cm-K)</td>
<td>4.9</td>
<td>3.2</td>
<td>0.35</td>
<td>0.15</td>
<td>0.5</td>
</tr>
<tr>
<td>TCE (ppm/K)</td>
<td>4.2</td>
<td>2.9</td>
<td>2.8</td>
<td>3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

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### 3. TEST SETUP AND CHARACTERIZATION

The fabricated devices were wire-bonded onto a square-wave oscillator (SWO) board (Figure 4), which forms an oscillator to force the DETF into resonance in air despite the presence of large feed-through capacitance [3]. The strain sensitivity of the sensor was characterized by applying axial force on the DETF using an on-chip electrostatic actuator. The axial force can be equated to an equivalent strain. The sensors were tested for strain resolution at various bandwidths, and also for high temperature operation. The phase noise of the strain sensor measured using Agilent E4440A Spectrum Analyzer were used to compute the strain resolution. For the temperature testing, a specialized high temperature test setup that locally heats the fabricated device up to 600°C in air is used (Figure 5). An IR lamp (SpotIR Model 4085, Research, Inc.) was placed underneath the oscillator board with its focal point focusing on the backside of the die. A heatsink and heat-resistant insulation were aligned in-between to prevent the electronics and circuit board from over-heating.

![Figure 2: Process flow of the main fabrication steps](image-url)
4. RESULTS AND DISCUSSION

Several dice were taken from different locations on the same wafer for testing. The poly-SiC BDETFs without the on-chip electrostatic actuator have resonance frequencies between 204 and 207 kHz in air. The variation in resonance frequency is attributed to the non-uniformity of thin film deposition and etching across the wafer. To the first order, the resonant frequency of the poly-SiC BDETF is proportional to the applied strain. The sensitivity of the resonant frequency to applied strain is measured to be 68Hz/με. The phase noise testing was carried out at room temperature to obtain the phase noise density, which is used to compute the strain resolution according to the equation (1)

\[ \varepsilon_{res} = \left( \frac{\partial f}{\partial \varepsilon} \right)^{-1} \sqrt{\frac{1}{BW} \int_{0}^{BW} \phi(f_c) df_c} \]  

where \( f_c \) is the carrier offset frequency, BW is the bandwidth of interest and \( \phi \) is the measured phase noise density [12].

With the bias voltage set to 80V, the strain resolution was measured to be 0.045 με at a bandwidth of 10 kHz (Figure 6). This is comparable to the state-of-the-art silicon comb-drive DETF strain sensor [3].

Figure 7 shows the frequency response of the SiC strain sensor at various temperatures up to 618°C. Repeated testing of the same device shows that there is no degradation of the sensor performance under high temperature operation, confirming the viability of the sensor for elevated temperature operation. The change in resonance frequency of the sensors with temperature is attributed to the TCE mismatch between the silicon substrate and SiC device layer. The temperature sensitivity of the sensors will be reduced by implementing the all-SiC design to minimize the thermal mismatch between the layers.

![Figure 6: Strain resolution as a function of measurement bandwidth. Data taken at room temperature](image)
5. CONCLUSION

We present a poly-SiC BDETF strain gauge with a modified layer structure suitable for harsh environment applications. The strain gauge resonates in air with frequencies ranging from 204-207 kHz operating at 600°C. Furthermore, this device achieves a resolution of 0.045 με at a 10 kHz bandwidth, comparable to previously reported silicon-based strain sensors.

This strain gauge has potential applications in internal combustion engines, oil-drilling rigs, as well as gas turbines. However, to fully implement this technology for practical applications, high temperature electronics and robust packaging need to be developed. Future work will address all-SiC device, the integration of SiC electronics, robust packaging, and communication modules.

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References


