Silicon carbide resonant tuning fork for microsensing applications in high-temperature and high G-shock environments

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Abstract. We present the fabrication and testing of a silicon carbide balanced mass double-ended tuning fork that survives harsh environments without compromising the device strain sensitivity and resolution bandwidth. The device features a material stack that survives corrosive environments and enables high-temperature operation. To perform high-temperature testing, a specialized setup was constructed that allows the tuning fork to be characterized using traditional silicon electronics. The tuning fork has been operated at 600°C in the presence of dry steam for short durations. This tuning fork has also been tested to 64,000 G using a hard-launch, soft-catch shock implemented with a light gas gun. However, the device still has a strain sensitivity of 66 Hz/µε and strain resolution of 0.045 µε in a 10-kHz bandwidth. As such, this balanced-mass double-ended tuning fork can be used to create a variety of different sensors including strain gauges, accelerometers, gyroscopes, and pressure transducers. Given the adaptable fabrication process flow, this device could be useful to microelectromechanical systems (MEMS) designers creating sensors for a variety of different applications. © 2009 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3143192]

Subject terms: microelectromechanical systems (MEMS); silicon carbide (SiC); thermal effects; double ended tuning fork (DETF); harsh environment; high temperature; high shock; inertial; strain; sensors.

Paper 08138SSR received Aug. 15, 2008; revised manuscript received Mar. 10, 2009; accepted for publication Apr. 13, 2009; published online May 29, 2009.

1 Introduction

Silicon carbide (SiC) microsensors and actuators have potential applications in a variety of harsh environment situations. For example, SiC sensors have operated in corrosive high-temperature environments such as those experienced in automotive engine exhaust and those found inside engine cylinders. In addition, sensors have been designed to survive high shocks (>60,000 G) such as those found in avionic, space, and military applications. Since SiC sensors and electronics may operate at high temperatures (500°C), there is no need for active cooling systems to ensure operation, saving weight in critical avionic, hybrid, and electric automotive applications.

Such applications are possible because SiC has attractive thermal, chemical, and mechanical stability at elevated temperatures as well as a large bandgap suitable for high-temperature electronics. When compared to traditional microelectromechanical systems (MEMS) materials, such as silicon, SiC has a higher fracture toughness, which allows for the creation of MEMS devices able to survive higher shock events. Furthermore, silicon carbide has a higher Young’s modulus (E) than silicon, reducing the deflection of device layers experiencing high G load forces. As such, SiC is envisioned as a platform for a suite of harsh environment sensors such as accelerometers, gyroscopes, pressure sensors, and strain sensors.

The natural frequency of a double-ended tuning fork (DETF) changes due to applied strain and can be measured with an oscillator circuit. Used alone, the tuning fork is capable of measuring strain or temperature. Combining the tuning fork structure with a proof mass allows for the creation of an accelerometer or gyroscope. By placing a tuning fork on a diaphragm, one can create a pressure sensor. The versatility of the DETF is further improved when combined with a square wave oscillator circuit, allowing for high-resolution operation at atmospheric pressure. A silicon carbide tuning fork would allow for the creation of similar devices capable of working at higher temperatures and higher G-shocks, provided that it has a suitable strain resolution.

In this paper, we present a SiC balanced mass double-ended tuning fork (BDETF), which operates at high temperature, survives high G-shocks, and exhibits high strain resolution. A conceptual schematic of the device is shown in Fig. 1(a). It features a central node comb drive configuration, which minimizes torque applied to each tuning fork during shock events. However, the increased transduction area of a comb drive is maintained, which improves strain resolution. The fabricated sensors resonate in air with fre-
The resonator structure and principle of operation have been presented in detail by Azevedo et al. The previously reported process flow has been modified in this work to include key changes to improve the ability of these devices to withstand higher temperature, harsh environment operation. First, the routing layer is now created from silicon carbide to improve corrosion resistance. Second, 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 is replaced with a thick LPCVD low-stress silicon nitride (LSN). LSN is more corrosion-resistant than oxide and is used as protective coating by the integrated circuit (IC) industry and an etch mask for potassium hydroxide (KOH) etching. Moreover, LSN has higher thermal conductivity than oxide and its thermal coefficient of expansion (TCE) is significantly closer to SiC than oxide. These changes are expected to reduce the thermally induced stress mismatch between layers and improve the oxidation resistance, providing a strain sensor capable of working at 600°C. The material properties of different thin films are summarized in Table 1. The aforementioned changes will also accelerate the future transition of this device from Si substrate to SiC substrate, creating an all-SiC sensor.

The modified stack structure is shown in Fig. 2. It has several characteristics that could be useful to the designer in creating other structures. It is readily adaptable to a variety of fabrication situations, and it includes an electrical feedthrough layer to allow for the creation of more complicated and compact MEMS structures. Diaphragms, proof masses, and encapsulation layers can be incorporated into the existing structure with minimal changes. The maximum thickness of the poly-SiC device layer is limited by the selectivity of the etching process used. The minimum thickness is determined by the desired strain resolution, since the thickness is proportional to the motional current passing through the MEMS.

The stack used to create this tuning fork begins with a 100-mm-diam n-type (100) silicon wafer, and LSN (1.3 μm) is deposited by LPCVD. The first mask is used to pattern the thick LSN layer using a Lam Research Autoetcher 590. Next, thick poly-SiC and LPCVD poly-SiC layers are then patterned on the LTO using a Lam Research Autoetcher 590. Anchors and electrical contact points are then patterned on the LTO using a Lam Research Autoetcher 590. Next, thick poly-SiC (7 μm) is deposited by LPCVD at Case Western Reserve University using the process described in Ref. 1. Patterned using LTO as the etch mask to form the resonator.
structure. Lastly, the etch mask and sacrificial oxide are removed in vapor hydrofluoric acid to release the resonator structure.

Patterning of all the poly-SiC films in the fabrication process is performed with plasma etching in a commercial LAM TCP 9400 system, using an etch vapor mixture of HBr (125 sccm) and Cl₂ (75 sccm). The TCP forward and bias powers used are 300 W and 150 W, respectively, while the chamber pressure is kept at 12 mTorr for optimized etch selectivity and sufficient etch rate. The final fabricated device is shown in Fig. 1(b). Thicknesses of deposited thin films are measured using a Nanospec 4000 AFT spectrophotometer and confirmed by cross-sectional scanning electron microscopy (SEM). Resistivity values are obtained using a Tencor RS535C 4-point probe.

3 Test Setup and Characterization

The fabricated devices are wire-bonded onto a square-wave oscillator (SWO) board, shown in Fig. 3, which is able to drive the BDETF into resonance in air despite the presence of large feedthrough capacitance. The oscillator design is detailed in Ref. 8. The strain sensitivity of the sensor is characterized using an on-chip electrostatic actuator. The electrostatic actuator applies axial force to the BDETF that can be equated to an applied strain. The strain resolution of the sensors is computed from phase noise data, measured using an Agilent E4440A spectrum analyzer. Last, the dice are tested for high temperature operation and high shock survivability.

For the temperature testing, a specialized high-temperature test setup that locally heats the fabricated device up to 600°C in air was constructed and is shown in Fig. 4. This setup allows for the testing of the SiC BDETF with well-known, well-characterized silicon electronics, shown in Fig. 3. An IR lamp (SpotIR Model 4085, Research, Inc.) is placed underneath the oscillator board, with the focal point targeted on the backside of the die. A heat shield consisting of a steel plate and wood is added to prevent scattered radiation of the IR lamp from warming the silicon electronics. Also, a piece of Fiberfrax insulation with a hole in it is placed between the heat shield and printed circuit board (PCB). The insulation had a twofold purpose: preventing scattered radiation from hitting the board and providing support to the die during wire-bonding. To extend temperature testing time, a heat sink was added to the PCB to cool the silicon electronics. During experiments, compressed air is blown in the square tubing at 550 kPa to cool the silicon electronics. Before testing the MEMS dice, the setup was calibrated using a blank silicon die and thermocouple.

Dice are heated to various temperatures for approximately 100 seconds at a time, both with and without steam. Steam was used to accelerate potential oxidation at the elevated operating temperature. After 100 s, the signal from the square wave oscillator was lost. This could be due to the oscillator electronics being pushed out of tolerance, but after sufficient cooling, the board would begin working again. For the steam tests, the dice were allowed to heat up to 600°C (approximately 40 s) before applying dry steam. The dry steam was directed toward the MEMS die using a nozzle. Steam was created using a Top Innovations Model SF-290 multipurpose steamer. The steam was routed through copper tubing into a heater coil, which was kept at approximately 300°C to ensure that only dry steam is present around the device. A steam shield consisting of additional insulation was constructed to protect the PCB from steam.

For the shock testing, two samples were bonded to steel rounds using Vishay MBond 610 strain gauge epoxy. Once bonded, images of the dice and individual devices were taken to document the preshock condition of the sensor. The steel rounds were placed in a specialized testing holder used in conjunction with a light gas gun system at the Aerophysics Research Center located at the University of Alabama, Huntsville. Shock was applied to the dice using a hard-launch, soft-catch method, in which the dice were rapidly accelerated while leaving the gas gun and landed on soft padding. A schematic of the light gas gun system and the MEMS die holder are shown in Figs. 5(a) and 5(b), respectively. Acceleration data was determined by examining submillisecond high-speed video of the shock event and correlating distance and time data to acceleration. Images of the devices were taken after exposure to G-shock, and operation was tested by attempting to resonate the device.

4 Results

Several dice were taken from different locations on multiple wafers for testing. The poly-SiC BDETFs without the on-chip electrostatic actuator have resonance frequencies between 196 and 207 kHz in air. The variation in resonance frequency is attributed to the nonuniformity of thin film deposition and etching variation. The sensitivity of the BDETF resonant frequency to applied strain is measured to
be 66 Hz/µε. The phase noise density is measured at room temperature and is used to compute the strain resolution according to Eq. (1):

$$\varepsilon_{res} = \left[ \frac{1}{f_c} \left( \frac{df}{df} \right)^2 \left( \int_{0}^{BW} \phi(f_c) df_c \right)^{1/2} \right]^{1/2}$$

where $f_c$ is the carrier offset frequency, $BW$ is the bandwidth of interest, and $\phi$ is the measured phase noise density.\(^{(1)}\) The calculated strain resolution as a function of bandwidth for different applied bias voltages is shown in Fig. 6. With the bias voltage set to 80 V, the measured strain resolution is 0.045 µε at a bandwidth of 10 kHz. This is comparable to the state-of-the-art silicon comb-drive DETF strain sensor.\(^{(8)}\) However, implementing this high voltage in conjunction with application-specific circuitry could be difficult, so the strain resolution for other voltages was tested as well. For this particular device, the range of bias voltages was limited between 40 V and 80 V. Below 40 V, the motional current was too low for the oscillator circuit to work properly. Above 80 V, the electrostatic combs exhibit snap-in behavior. Decreasing the bias voltage reduces the motional current passing through the MEMS, and therefore reduces the strain resolution of the oscillator circuit. However, at 40 V, the BDETF is still capable of resolving 0.2 µε in a 10-kHz bandwidth.

The temperature sensitivity of this device for temperatures up to 600°C is shown in Fig. 7. The device has a temperature sensitivity of approximately $-17$ Hz/°C ($-91$ ppm/°C) from 26°C to 600°C. The change in resonance frequency of the BDETF is attributed to the temperature dependence of the modulus of elasticity and due to the coefficient of thermal expansion mismatch between the silicon substrate and silicon carbide structure. Fig. 8 shows a sample transient response curve of the BDETF in dry steam. In dry steam, the BDETF resonance frequency was 185.5 kHz at 592°C. This steady-state value matched that of the same resonator without steam to within the resolution limits of this experiment. This indicates that the resonator was not oxidized.

These results highlight that the resonant frequency is dependent on mechanically applied strain and thermomechanical effects. Several different authors have proposed temperature compensation methods for tuning forks. This includes passive compensation by using materials of different CTE,\(^{(9–22)}\) methods using pairs of resonators,\(^{(10,23)}\) or measuring two quantities\(^{(9)}\) or modes\(^{(24)}\) of the same resonator.
Example time-lapse photography of the G-shock testing is shown in Fig. 9. Videos of the shock event shown in Fig. 9 are used to extract the position and time data shown in Fig. 10. A superimposed line to help the reader identify the front of the MEMS die holder has been included in Fig. 9. A fourth-order polynomial curve was fit to the data. Taking the derivative twice, the acceleration on the die as a function of time was determined. There was an initial acceleration from zero to 64,000 G, but the video equipment was not sensitive enough to measure this phenomenon. Visually, no cracks, film delamination, or fracture was observed on or around the BDETF structure. The BDETF also successfully resonated within normal operational parameters after the shock event, indicating no damage had occurred.

5 Conclusion

A poly-SiC BDETF that resonates in air, operates at 600°C in steam, and survives shocks of 64,000 G has been presented. This device achieves a resolution of 0.045 με in a 10-kHz bandwidth, which is comparable to previously reported silicon-based strain sensors. This poly-SiC BDETF utilizes a layer structure suitable for harsh environment applications that may be reconfigured for a number of different sensing applications. Given the high strain resolution and sensitivity of this device, it could be used to create pressure sensors, accelerometers, and gyroscopes. All of these structures require additional proof masses and diaphragms, which need special design attention to ensure that these could also survive high shocks. However, since this BDETF is capable of surviving the high-temperature, high-G-shock environment, the designer can utilize this structure and focus on other design aspects of the various sensors.

The current design uses a low Q tuning fork with an SWO, which is optimized to reduce phase noise in large bandwidth. Future work will focus on improving the tuning fork structure by reducing gap sizes and implementing vacuum encapsulation. These improvements will allow for other oscillator topologies that use smaller bias voltages. Furthermore, the addition of encapsulation will also protect the structure from particulates, which cause shorting. Also, by including high-temperature electronics, long-term, high-temperature testing will be enabled. Should the electronics be directly integrated, feedthrough capacitance will be reduced, further improving the performance of this device.

Acknowledgments

This project is funded by DARPA Contract No. NBCH1050002. The BDETF was fabricated in the UC Berkeley Microfabrication Laboratory. The authors would like to thank the Aerophysics Research Center at the University of Alabama, Huntsville, for their assistance in the high-G-shock testing. The authors would also like to thank Dr. Anand Jog for many helpful discussions.

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