Abstract—Temporal drifts in zero pressure offset voltage, $V_{oz}$, observed in piezoresistive silicon carbide (SiC) pressure sensors at 600 °C were significantly suppressed to allow reliable operation. By modifying the bondpad/contact metallization, the $V_{oz}$ relative drift velocity at 600 °C was suppressed to within ±0.5 mV.hr$^{-1}$, for over 1000 hours. Microstructural changes within the contact metallization were analyzed with Auger Electron Spectroscopy (AES) and Scanning Electron Microscopy (SEM). This metallization scheme may improve SiC pressure sensor reliability in short duration ground/flight tests and lower temperature (~300 °C) remote pressure monitoring (i.e., geothermal, and deep well drilling).

I. INTRODUCTION

Robust and reliable sensors are needed for the measurement and monitoring of pressure conditions in aggressive environments that in some cases have combinations of high temperature (>500 °C), corrosive chemicals, vibration, and radiation [1, 2]. These measurements are largely due to the need for increased safety in flight, validation of next generation engine codes, and pressure monitoring in remote stations. For example, in the ground testing of jet engine combustion parameters, determination of the onset of thermo-acoustic instability that occurs during combustion is desired [3]. The conditions leading to such instability, such as pressure fluctuation, must be quantified in order to mitigate its expansion that could potential lead to the damage of critical engine components during flight [4, 5]. Pressure monitoring is also an integral of safety protocols in chemical processing and nuclear power plants to guard against over-pressure ruptures that precede explosions, or the leaking of radioactive materials, respectively [6, 7]. NASA and other space exploration entities need robust and reliable pressure sensors for long duration science missions to planets such as Venus, which has a corrosive atmosphere and high temperature (~470 °C) [8]. In oil and geothermal wells, where the temperature is less than 300 °C, the high cost of equipment downtime has made it imperative to develop reliable and robust sensors that can survive unsupervised for prolonged periods in the wells [9]. Future aerospace propulsion systems are being produced using performance-optimized computational fluid dynamic codes. The accuracy uncertainty of these codes in high temperature combustion regimes is still high, thereby making their experimental validation imperative.

The integrity of a pressure sensor is highly dependent on the stability of the reference zero output voltage, $V_{oz}$, after initial calibration and during the entire period of the test campaign. The degree of $V_{oz}$ drift that occurs during measurement determines sensor accuracy. However, it must be understood that there is a fundamental difference between the uncompensated output of sensor at zero pressure, thermal null shift (temperature effect on $V_{oz}$), and temporal $V_{oz}$ drift at fixed temperature (henceforth termed $V_{oz}$ drift). The first two parameters are characteristics of the sensor and repeatable, hence, their effects are routinely resolved by the implementation of temperature compensation schemes. On the other hand, $V_{oz}$ drift is typically manifested by either fluctuation around the reference voltage or a systematic irreversible deviation or change from the initial reference value. This is particularly important in remote pressure monitoring, process control in chemical or nuclear plants, and in active control of combustion. These are applications in which the sensor is pre-calibrated before being used for real-time, autonomous decision making on the basis of pre-determined pressure thresholds. A sensor with $V_{oz}$ drift is basically useless for such sensitive applications, particularly where safety is the primary goal. Such temporal drift is the most difficult parameter to suppress and has been identified as the major cause of sensor failures in these environments.
because it takes the sensors out of the irreversible calibration. The sensor may, however, be applicable for short duration tests (i.e., engine ground tests) if the relative $V_{ac}$ drift velocity is a small fraction of the sensor fullscale output (FSO) at the operating temperature. Quantifying the velocity of such small drift would allow for a comparison between the pre- and post-test reference voltages and correction without loss of measurement integrity.

Combinations of thermal, physical and radiation effects interact to cause temporal $V_{ac}$ drift. These effects are more pronounced in conventional semiconductor piezoresistive pressure sensors, such as silicon, as the temperature increases beyond $125{^\circ}C$, thereby requiring complex temperature compensation schemes and costly packaging with plumbing for cooling. However, because $V_{ac}$ drift is due to thermodynamics and reaction kinetics, it does not lend itself to effective compensation [10-12].

In this work, we are particularly interested in suppressing the temporal $V_{ac}$ drift by engineering the contact metallization and metallurgical joints so that the resistance change is small over time at any given temperature. A suppression of such effect to the level that the SiC piezoresistive pressure sensors can be acceptable for high temperature operation would be considered a preliminary success.

![Cross section illustration of the SiC pressure sensor showing the location of the piezoresistive elements in relation to the diaphragm and contact metallization; b) equivalent closed Wheatstone bridge circuit, with the uncoupled contact resistance, and c) the contact metallization stack corresponding to $R_m$. The Pt thicknesses in version-1 and 2 are 50 nm and 200 nm, respectively. The first Ti/TaSi$_2$ layers are simultaneously annealed in both cases before subsequent depositions.](image)

**Fig. 1.** a) Cross section illustration of the SiC pressure sensor showing the location of the piezoresistive elements in relation to the diaphragm and contact metallization; b) equivalent closed Wheatstone bridge circuit, with the uncoupled contact resistance, and c) the contact metallization stack corresponding to $R_m$. The Pt thicknesses in version-1 and 2 are 50 nm and 200 nm, respectively. The first Ti/TaSi$_2$ layers are simultaneously annealed in both cases before subsequent depositions.

**II. EFFECT OF CONTACT RESISTANCE ON OFFSET DRIFT**

The thermo-mechanical and -chemical characteristics of SiC, in addition to its superior radiation hardness relative to silicon [13], makes it a more viable material for harsh environment sensing applications. Piezoresistive SiC pressure sensor have been previously reported to operate at $600{^\circ}C$. However, it suffered from $V_{ac}$ drift, which became severe with increasing temperature. Okojie et al. [14] had previously reported $V_{ac}$ drifts in SiC pressure sensors at $500{^\circ}C$, which provided an insight to the correlation between the contact metallization at the bondpad and the observed drift. Since the target environment for these sensors is between $300{^\circ}C$ (i.e., long-term, remote pressure monitoring in geothermal and oil wells, and in nuclear power plants) and $600{^\circ}C$ (i.e., short duration engine ground and flight tests), it becomes necessary to develop SiC pressure sensors with significantly suppressed drifts within that temperature regime.

The cross section illustration of the SiC pressure sensor depicting the contact metallization and the piezoresistors is shown in Fig. 1 (a), while Fig. 1 (b) is the equivalent closed Wheatstone bridge circuit in which the resistance of the contact metallization/bondpad/external wire metallurgical joint contact, denoted $R_m$, is uncoupled from the piezoresistors. In this analysis, we are primarily interested in $R_m$, which is illustrated in Fig. 1 (c). The sensor equivalent output resistance is shown in Fig. 2, in terms of the sensing element equivalent resistance, $R_{eq}$, and the contact/metallurgical joint resistance, $R_{cm}$. In SiC, because of its thermodynamic stability, temporal changes in the sensing elements ($R_{eq}$) are generally reproducible and do not extensively deviate from known thermophysical characteristics. Topics relating to piezoresistance in general, with regard to temperature coefficients of resistance, gage factor, sensitivity, and offset, and their effects on sensor performance have been exhaustively studied and reported in literature. They form the basis of various temperature compensation methodologies. However, as was determined in [14] for SiC, and [12, 15] for silicon, changes in $R_{cm}$ are spurious and irreversible, leading to significant drift of $V_{ac}$.

Expressed mathematically,

$$R_{cm}(T, t) = \frac{\rho_r(T, t)}{A} + R_m(T, t)$$  \hspace{1cm} (1)

where $\rho_r$ is the specific contact resistivity ($\Omega$-cm$^2$) of the contact metallization to SiC, $T$ is the soak temperature (${^\circ}C$), $t$ is soak time (hr), and $A$ is the effective bondpad area (cm$^2$). The $R_{cm}$ is primarily driven by thermodynamic and reaction kinetics at the metallurgical junctions. Hence, any asymmetric temperature- and time-dependent microstructural
and phase transformations occurring within the four $R_{um}$'s (being a closed bridge) are bound to introduce imbalances that would appear in the output impedance, $R_{out}$, consequently appearing as drift in the voltage output of Fig. 1 (b).

### III. EXPERIMENTAL SETUP

Two sets of 4H-SiC piezoresistive pressure sensors were fabricated on the same wafer. Both sets had the contact metallization as shown in Fig. 1 (c): Ti (100 nm)/TaSi$_2$ (400 nm)/TaSi$_2$ (400 nm)/Pt/Ti (5 nm)/Au (2 µm), with Ti being the first layer deposited on the SiC. Before subsequent deposition, the first two layers were rapid thermal annealed at 1000 °C in argon for 3 seconds. The next pair of layers was deposited, patterned, and furnace annealed at 650 °C in argon for 30 minutes. The thickness of the Pt in version-1 (V-1) was 50 nm, while that of version-2 (V-2) was 200 nm. Finally, Ti/Au deposition was performed to cap the contacts. The Au facilitated excellent wettability to the Au die-attach paste that was used as the metallurgical joint between the bondpads and the connecting wires during packaging, as shown in Fig. 3. Because the piezoresistors were passivated with SiO$_2$, no Au paste was in electrical contact with them. Selected sensors with V-1 metallization were initially soaked at 588 °C for 1000 hrs, followed by 200 hrs at 600 °C. The first 200 hours was the burn-in period. The sensors in V-2 set were soaked at 600 °C for 1000 hrs. The $V_{oz}$ of both batches were recorded over time at fixed temperature. During testing, key parameters, such as the $V_{oz}$, output resistance, $R_{out}$, and FSO at 500 psi, were intermittently monitored. In parallel, unpackaged V-1 and V-2 metalized sensors from the same wafer as the packaged ones were soaked at 600 °C in atmospheric oven for 1000 hrs. These tracking sensor sets, which had no Au die-attach paste, were extracted intermittently and analyzed using Auger Electron Spectroscopy (AES) and Field Emission Scanning Electron Microscopy (FE-SEM).

### IV. RESULTS AND DISCUSSION

In Fig. 4 (a), the $V_{oz}$ at 588 °C of a representative V-1 sensor is seen to drift downward over time, with a relative hourly drift velocity to be within $\pm 0.5$ mV.hr$^{-1}$. The maximum deviation from the initial reference (108.9 mV, 200 hrs) was 92.34 mV. The sensor $R_o$ at this temperature is also seen to be increasing with time at temperature, as shown in Fig. 4 (b). A dramatic drop in the $V_{oz}$ accompanied by increase in drift velocity was observed when the temperature}

![Fig. 3. FE-SEM micrograph of section of pressure sensor showing the SiC/contact metallization/die-attach/wire. No Au was in contact with the piezoresistors outside the bondpad area.](image)

![Fig. 4. Temperature and time dependent response of a) zero offset, b) output resistance of 4H-SiC pressure sensor with V-1 contact metallization. The spikes in the $\Delta V_{oz}.hr^{-1}$ plots are due to data not recorded on weekends; c) AES profile indicates that by 1000 hrs, Au agglomeration at the SiC interface has occurred (arrowed).](image)
was raised to 600 °C, with $R_o$ also rapidly increasing. These changes coincided with microstructural changes occurring within the metallization. The AES depth profile, shown in Fig. 4 (c), was from the tracking sensor sample. It revealed the agglomeration of the top layer Au at the SiC interface, essentially mixing with the Ti ohmic contact layer. The metallurgical boundaries of the contact metallization have become indistinguishable. As best explained in (1), such microstructural changes in the metallization are bound to affect the $\rho_c$. Because this is a time-dependent kinetic reaction, it would result in $V_{ac}$ drift.

In contrast, the $V_{ac}$ of V-2 sensors exhibited better stability over time, despite being soaked solely at 600 °C for the entire 1000 hrs (Fig. 5a). There was, however, an indication of runaway drift away during the last hundred hours. With regard to the hourly relative drift velocity, it is seen to lie deep inside the $\pm 0.5 \text{ mV/hr}^{-1}$ domain. The corresponding output resistance, shown in Fig 5 (b), also exhibited a smaller change compared to the V-1 of Fig. 4 (b). The AES depth profile from the tracking sensor sample shows the Ti-based ohmic contact to the SiC to be intact, with no significant presence of Au [Fig. 5 (c)]. Unlike V-1, there is no evidence of Au diffusion to the SiC interface and the metallurgical reaction zones remain well defined.

Another set of V-2 sensors that was evaluated had stud-bumped Au ball bonds sandwiched between the bondpad and die-attach. The strategy was to implement Au-Au thermocompression bonding as opposed to die-attach pasting. It is believed to prevent the die-attach, known for its mobile ion content, from intimately contacting the device. After packaging, the sensor was initially burned in at 650 °C for 20 hours, followed by the long term test. This was done to accelerate the completion of the intermetallic reactions, thereby minimizing further changes in $R_{on}$ with time. The representative plots of the $V_{ac}$ and $R_{on}$ are shown in Fig 6 (a) and (b), respectively. During the 1200 hours soak time at 600 °C, the $V_{ac}$ drift is seen to straddle the initial reference $V_{ac}$ (358.52 mV, 20 hrs) with an upper and lower limit drift of 361.66 mV and 350.65 mV, respectively (excluding spike events that were results of not taking data on weekends) as illustrated by the drift band. That amounts to a 5 % deviation from reference after 1200 hours. No runaway drift occurred. In terms of the hourly relative drift velocity, it remained well inside $\pm 0.5 \text{ mV/hr}^{-1}$. This is very significant because it reflects sensor accuracy when used in short duration engine or flight tests. At 600 °C, the sensitivity of SiC piezoresistive pressure sensors typically drops by 60 % of its room temperature value [16]. Therefore for a 500 psi-rated SiC pressure sensor having a 30 mV FSO at room temperature, it will drop to about 12 mV at 600 °C. Taking into consideration the relative $V_{ac}$ drift velocity, the maximum measurement error will be 4 % FSO (600 °C).

The above results, in terms of sample sets V-1 and V-2 metallization, can be explained by the differences in the microstructure of the platinum silicide that was formed. Platinum reacts with the silicon in the TaSi$_2$ layer in a reaction chain that proceeds thus: Pt $\rightarrow$ Pt$_2$Si $\rightarrow$ PtSi [17]. PtSi has excellent diffusion barrier properties in preventing gold diffusion through the underlying metal layers to the SiC interface. Batch V-1 sensors had thinner Pt layer, hence formed a thinner layer of platinum silicide having high grain boundary density. As the temperature increases, it provides a broad path for Au, through Au-Si eutectic diffusion couple, to diffuse to the SiC interface, thereby making the contact resistance unstable. On the other hand, V-2 with the thicker Pt layers formed a thicker and more stable variation of its

![Fig. 5. Temperature and time dependent response of a) zero pressure offset, b) output resistance of 4H-SiC pressure sensor with V-2 contact metallization; c) after 1000 hrs, no Au agglomeration is observed at the SiC interface.](image-url)
Fig. 6. a) Temperature and time dependent response of zero pressure offset and b) corresponding output resistance of 4H-SiC pressure sensor with V-2 contact metallization having stud-bump ball bond between bondpad and die-attach. Note: The spikes in the output resistance were due to connection maintenance.

silicide with less grain boundary density. It has been found from experiments to be reported in the future that the Pt thickness must be controlled to give optimum result. Too thick or too thin layers tend to present adverse effects on the electrical stability of the sensor caused by the agglomeration at the SiC interface of a combination of Pt and Au. As shown in the FE-SEM of Figs. 7 (a) and (b) of the unpackaged tracking samples of V-1 and V-2 metallization, there was a dramatic difference in microstructural characteristics of the tracking sensor samples after soaking at 600 °C for 1000 hours. Both V-1 and V-2 showed the formation of Au/Si eutectic. It has been determined that Au/Si eutectic forms starting at 400°C [17]. In V-1, the thin platinum silicide formed by decomposing TaSi2, was disrupted by the Au/Si eutectic. With the diffusion barrier breached, Au was able to migrate and agglomerate at the SiC interface. With regard to V-2, a thicker platinum silicide with low grain boundary density was formed. It is seen in Fig. 7 (b) to effectively prevent Au/Si diffusion, thereby allowing the SiC interface to be free from Au. It is believed that the absence of Au at the SiC interface preserved the stability of the Ti ohmic contact, thereby reducing the Voz drift relative to V-1. Based on these results, the performance characteristics of a SiC pressure sensor with V-2 metallization incorporating stud bump was extracted and presented in Table I.

TABLE 1: OPERATING CHARACTERISTICS OF THE STUD-BUMPED SiC PRESSURE SENSOR WITH V-2 METALLIZATION.

| Parameter                              | Value                                      |
|----------------------------------------|--------------------------------------------|
| Excitation Voltage (V)                 | 5                                          |
| Static Pressure Range (psi)            | 500                                        |
| Max. Rated Operating Temperature (°C)  | 600                                        |
| Full Scale Output (mV)                 | 30                                         |
| Pressure Sensitivity (μV/V/psi)        | 12 @ 25 °C; 4.8 @ 600 °C                   |
| Linearity (%FSO)                       | 0.1 @ 25 °C; 0.46 @ 600 °C                |
| Maximum Temporal Drift (% Offset)      | 4                                          |
| Maximum Hourly Relative Offset Drift (mV.hr⁻¹) | ± 0.5                                    |

Fig. 7. FE-SEM cross section after 1000 hours at 600 °C of a) V-1 metallization shows Au/Si eutectic diffusion through the thin Pt layer, and TaSi2 layer, leading to Au agglomeration at the SiC interface; b) V-2 metallization shows thick PtSi diffusion barrier against the Au/Si eutectic diffusion couple, thus preventing Au from reaching the SiC interface.

V. CONCLUSION

As the test environment temperature increases, temporal drifts in the zero pressure offset in piezoresistors cause the sensors to become progressively more unstable. It has been determined that such temporal drift is due to enhance...
thermodynamic activities occurring within the sensor metallurgical reaction zones of the sensor. By optimizing the contact metallization of the SiC piezoresistive pressure sensors, the hourly relative drift velocity of the offset voltage was significantly suppressed to within 5 \% of the initial reference and about 4 \% FSO at 600 °C. Because the voltage offset temporal drift is the result of enhanced reaction as temperature increases, it is expected to reduce at lower temperatures. By burning-in the sensor at above the operating temperature, the result shows a considerable suppression of the drift. Consequently, it is now possible to apply the SiC pressure sensors for both short duration engine ground and flight tests. For remote applications, consideration should be given to the temperature of the environment that corresponds to the lowest acceptable sensor drift velocity.

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