Characterization of n-Type β-SiC as a Piezoresistor

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Abstract—SiC is currently being investigated for device applications involving high temperatures. In this paper, the properties of n-type β-SiC relevant to piezoresistive devices, namely the gauge factor (GF) and temperature coefficient of resistivity (TCR), are characterized for several doping levels. The maximum gauge factor observed was −31.8 for unintentionally doped \((10^{14}-10^{17}/\text{cm}^3)\) material. This gauge factor decreases with temperature to approximately half its room-temperature value at 450°C. Unintentionally doped SiC has a roughly constant TCR of 0.72%/{°C} over the range 25-800°C and exhibits full impurity ionization at room temperature. Degenerately doped gauges \((N_d = 10^{20}/\text{cm}^3)\) exhibited a lower gauge factor \((-12.7)\), with a more constant temperature behavior and a lower TCR \((0.04\text{%}/°C)\). The mechanisms of the piezoresistive effect and TCR in n-SiC are discussed, as well as their application towards sensors.

I. INTRODUCTION

Silicon Carbide has long been considered a potentially useful semiconductor for high-temperature applications due to its unique properties, such as its wide bandgap, high thermal conductivity, and high melting point [1]. However, early efforts in SiC devices were unsuccessful, due to the lack of high-quality material. Recent breakthroughs in crystal growth [2], [3] have generated renewed interest in SiC, leading to the development of high-temperature devices, such as p-n-junction diodes and MOSFET’s [4], [5]. However, very little research has been done on sensor applications for SiC, with no previous work done on β-SiC sensors.

Silicon-based piezoresistive sensors have been useful for measurement of pressure and strain in many different environments, since silicon elements exhibit a much higher strain sensitivity than conventional metallic foil gauges. However, at elevated temperatures \((>600°C)\), silicon is limited because it deforms plastically under minimal load [6]. Therefore, it is necessary to use a higher temperature material, such as SiC, in sensor applications above 600°C. Such applications include pressure measurements in jet and rocket engines, wind tunnels, as well as material processing and strain measurement on the outer hulls of aircraft.

The piezoresistive properties of SiC have not yet been fully characterized. Some early Russian work was done on the piezoresistance of α-SiC, which has a large piezoresistive effect (e.g., high-resistivity n-type 6H-SiC has \(\pi_{11} = -142 \times 10^{-12} \text{cm}^2/\text{dyne at 273 K} \) [7]. However, just one study was done on the piezoresistance of cubic SiC, which reported only the hydrostatic pressure coefficient, \(\pi_{11} + 2\pi_{12}\), but did not examine the two coefficients \(\pi_{11}\) and \(\pi_{12}\) separately [8].

In this paper, the gauge factor (GF) and temperature coefficient of resistivity (TCR) of n-type β-SiC are characterized in order to determine the applicability of the material for sensors. This characterization includes measurement of the components of the piezoresistive tensor for β-SiC to determine which gauge orientation has the largest sensitivity. Furthermore, the dependence of the piezoresistance on temperature, strain, and doping level are examined. The TCR (temperature coefficient of resistivity) of n-type β-SiC is reported for the temperatures of interest. Knowledge of these parameters allows the design of a high-temperature strain-sensing element from SiC that can be temperature-compensated to yield a temperature-independent output. Such a strain gauge can be used as the "sensor" in a monolithic diaphragm structure, used to measure pressure.

II. SEMICONDUCTOR STRAIN GAUGES

Semiconductor strain gauges are based on the piezoresistive effect which is defined as the tensor relationship between applied stress and change in resistivity

\[
\frac{\delta \rho}{\rho} = \pi_{ijkl} \sigma_{kl}
\]

where \(\rho = \text{resistivity}, \sigma = \text{stress}, \text{and } \pi = \text{piezoresistance} \). In the case of a cubic semiconductor, such as β-SiC, the fourth-order piezoresistance tensor has three independent coefficients: \(\pi_{11}, \pi_{12}, \text{and } \pi_{44} \). The change in resistance can also be expressed in terms of strain by using the gauge factor (GF), which is defined as

\[
GF = \frac{\delta R}{\epsilon R}
\]

where \(\epsilon = \text{strain} \). A positive gauge factor corresponds to an increase in resistance with tensile strain while a negative GF signifies a decrease. The gauge factor is a scalar quantity, not a tensor, but is dependent on the crystallographic direction and is related to the piezoresistive coefficients by Young's modulus, which couples stress and strain, and some small dimensional corrections [9]. The temperature fluctuation of the gauge factor is referred to
as the TCGF, which is defined as

\[ \text{TCGF} = \frac{\text{GF}(T) - \text{GF}(T_{\text{ref}})}{\text{GF}(T_{\text{ref}})(T - T_{\text{ref}})} \]

Knowledge of the TCGF is necessary to achieve temperature compensation of the sensing elements in a transducer.

### III. Fabrication and Testing of β-SiC Strain Gauges

In order to measure the gauge factor of SiC, strain gauges of several different orientations were fabricated. The gauge orientations, which are shown in Fig. 1, correspond to three different combinations of the piezoresistive coefficients and hence can determine the relative magnitudes of these coefficients.

Epitaxial layers of β-SiC, 10 μm thick, were grown by CVD on (100) silicon substrates at the NASA Lewis Research Center by previously described means [10]. When no dopant gas was added to the system, the samples were n-type with resistivities ranging between 0.1–1.0 Ω·cm and carrier concentrations in the range of \(10^{16}-10^{17} \text{ cm}^{-3}\). In order to obtain lower resistivity wafers (0.01–0.001 Ω·cm, \(10^{18}-10^{19} \text{ cm}^{-3}\)), nitrogen was added to the gas mix in concentrations ranging between 29 and 170 ppm.

The SiC on Si samples were then metallized and patterned into rectangular strips. Each SiC strip had contacts at each end to which gold lead wires were attached using ultrasonic bonding. The SiC film and leads were then encapsulated in black wax and the silicon substrates were selectively removed with HF: HNO₃ leaving thin free-standing SiC strips which would be used as strain gauges. For measurements where contact resistance was significant (including all TCR measurements), Kelvin gauges were used.

Gauge-factor measurements were done using the bending beam technique. Namely, the strain gauges were mounted onto a steel cantilever beam, and the beam was bent, producing a uniaxial surface strain across the length of the beam. Assuming that the thickness of the beam was much greater than the gauge thickness and that the mounting agent transmitted the strain effectively, the strain in the gauge would be uniaxial, following that of the surface of the beam. In these experiments, p-Si gauges of known gauge factor were mounted alongside the SiC gauges. The gauge factors measured for the SiC gauges were within 5–10% of the values reported in the literature, which indicates the accuracy of these experiments.

The mounting agent used for room-temperature measurements was epoxylite 8121 strain gauge cement, which cures at 90°C [11]. For the high-temperature measurements, the gauges were thermally mounted to the beam by melting glass frits between the gauge and the beam at temperatures of \(\approx 500°C\). The thermal mismatch between the SiC gauges (CTE = 2.6 ppm/°C) and the steel cantilever beam (CTE = 10.8 ppm/°C) caused the mounted gauges to be placed into compression upon cooling to room temperature. This compression caused an effective increase in the room-temperature gauge factor, due to the nonlinearity of the piezoresistive effect with strain.

### IV. Gauge Factor of SiC: Crystallographic Dependence

The room-temperature gauge factors for n-type β-SiC are listed in Table I along with the GF's of n-Si calculated from the literature [9]. For high-resistivity SiC, configuration (a) (Fig. 1) has the largest magnitude, indicating that \(\pi_{11}\) is the largest of the piezoresistive coefficients for both n-SiC and n-Si. This suggests that a gauge of orientation (a) will have the maximum sensitivity and therefore be the most useful for sensors. The magnitude of the gauge factor of SiC decreases with doping level, but, as we will show, exhibits a more constant temperature behavior. Fig. 2 shows the variation of the GF with strain up to a strain of 2000 ppm for a gauge of configuration in Fig. 1(a) with a resistivity of 0.7 Ω·cm. The nonlinearity of the GF with strain equals 0.4%/100 ppm in Fig. 1(a) configuration with the magnitude of the GF's decreasing with tension and increasing under compression.

There are several theories found in the literature for the piezoresistive effect in semiconductors. In n-silicon, as well as most other n-type semiconductors, the one that applies is the electron transfer effect [12]. This theory relates the change in resistivity to a redistribution of electrons among the multivalleys in momentum space. Fig. 3 is a diagram of four of the six multivalleys found in a cubic crystal. In this figure, the multivalley minima are all along a major crystallographic axis \(\langle 100\rangle\). The electron mobility is highly anisotropic within the valleys, but the symmetry of the six valleys causes the net mobility to be uniform. The application of a tensile strain in the \(\langle 100\rangle\) direction will cause the multivalley minima along the x-direction to rise in energy, while those in the y- and z-directions will drop. This situation is depicted by the
TABLE I

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity (Ω·cm)</th>
<th>GF (Fig. 1(a))</th>
<th>GF (Fig. 1(b))</th>
<th>GF (Fig. 1(c))</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-β-SiC</td>
<td>0.7</td>
<td>-31.8</td>
<td>+19.2</td>
<td>-3.7</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>-26.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>-12.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-Si</td>
<td>11.0</td>
<td>-133.0</td>
<td>+68.3</td>
<td>-52.0</td>
</tr>
</tbody>
</table>

Corresponding piezoresistive coefficients

\[ \pi_{11}, \pi_{12}, \pi_{44} \]

**Fig. 2.** Resistance versus strain for n-type β-SiC strain gauges (0.7 Ω·cm) of the configuration of Fig. 1(a) mounted with Epoxylite 8121 strain gauge cement.

**Fig. 3.** Energy surfaces in momentum space. Under zero strain, the multivalleys are symmetric. When a tensile strain is applied in the (100) direction, the minima in the (100) direction rise in energy while those in the (010) and (001) direction drop. This causes an electron transfer which results in an anisotropic mobility. The strained energy surfaces are represented by dashed ellipses.

dotted lines. The energy difference will cause a redistribution of the electrons between the potential wells. In a resistivity measurement along the (100) direction, more electrons will have mobilities equal to \( \mu_1 \), the transverse mobility, than \( \mu_1 \), the longitudinal mobility. This causes a net change in the resistivity.

For a lightly doped sample, Boltzmann statistics can be used to estimate the value of the change in resistivity for strains applied in different configurations (e.g., Fig. 1). This analysis has been done [12], and the results indicate that for a cubic semiconductor with its multivalley minima in the (100) direction, \( \pi_{11} \) will be the largest coefficient with \( \pi_{12} = -1/2 \pi_{11} \) and \( \pi_{44} = 0 \). It is easy to visualize why \( \pi_{44} \), the shearing coefficient, plays no role. A shearing strain is equal to a tension in the (111) direction and an equal and opposite compression at 90°, in the (111) direction. This type of shear will cause all of the six multivalleys to deform in the same manner, preserving the crystal symmetry.

The electron transfer mechanism has been accepted as the primary effect for n-Si, which has its multivalleys in the (100) direction and piezoresistive coefficients in accord with the theory. Electron cyclotron resonance experiments on β-SiC [13] have shown that it also has its multivalleys in the (100) direction and a large mobility anisotropy exists within the valleys. The data in Table I show that the piezoresistive coefficients of β-SiC (0.7 Ω·cm) follow the theory closely with \( \pi_{12} = -0.6 \pi_{11} \) and \( \pi_{44} < \pi_{11}, \pi_{12} \). Thus it is reasonable to assume that the electron transfer effect is the dominant mechanism for n-type β-SiC, with smaller secondary effects possibly playing a role as well.

V. TEMPERATURE VARIATION OF THE GAUGE FACTOR

**Fig. 4** plots the gauge factor (configuration of Fig. 1(a)) versus temperature for two nitrogen doping levels, \( 10^{18} \) and \( 10^{20} \) cm\(^{-3} \). Initially, the gauge factor of the \( 10^{18} \) cm\(^{-3} \) material shows a large decrease with temperature, but starts to level off to a value of \( \approx -18 \) at 400°C. This result is similar to the behavior of lightly doped silicon strain gauges which exhibit a large temperature dependence at low temperatures and a reduced temperature dependence at higher temperatures [15].

For degenerate doping (\( 10^{20} \) cm\(^{-3} \)), the temperature variation of the gauge factor is reduced, with a roughly constant gauge factor of \( \approx -9 \) at temperatures above 300°C. In fact, most of the temperature variation in the degenerate gauges in Fig. 4 is probably due to an increase
in the low-temperature GFs, due to compression caused by high-temperature mounting. Similar gauges, mounted at low temperatures with epoxy, have room-temperature GF of -8.7. This gauge factor is very close to the gauge factors exhibited in Fig. 4 near the sealing temperature of the glass-mounting agent, at which point the compression effects are small. It should be noted that the degenerately doped gauges of Fig. 4 were not Kelvin gauges. Measurements of degenerate SiC gauges with Kelvin contacts (Table I) indicate that the values of the GF's of the degenerately doped gauges of Fig. 4 are reduced by \( \approx 25\% \) due to the contact resistance.

The electron transfer mechanism for the piezoresistive effect in semiconductors predicts a \( 1/kT \) dependence of the piezoresistive coefficients with temperature [12]. This temperature dependence is most valid at low temperatures and low doping levels. For highly doped semiconductors, both the magnitude of the piezoresistance and its dependence on temperature is reduced. In the case of extreme degeneracy, as is seen in metals, the piezoresistive effect becomes smaller than resistance changes due to deviations in dimensionality of the gauges. However, degenerately doped semiconductors have large gauge factors compared to metals while being significantly more temperature-independent than lower doped semiconductors. The combination of sensitivity and stability make degenerately doped semiconductors generally more useful as strain-sensing elements than low-doped materials.

All of the doping levels in n-type SiC exhibit a more temperature-independent gauge factor at temperatures above 200°C. At temperatures approaching 500°C, the gauge factor appears to be almost constant with temperature. This behavior indicates that at even higher temperatures, the gauge factor may retain this constant value. The gauge factor of silicon at high temperatures is between 40–60 depending on the doping level, while those of metallic gauges are between 1–2. Since the magnitude of the SiC GF at high temperatures equals 10–18, it appears that n-type β-SiC has a sufficiently high sensitivity to be useful at temperatures where silicon cannot be used.

### VI. TCR (Temperature Coefficient of Resistivity) of n-Type β-SiC

In order to evaluate a piezoresistive sensing material that will be used over a wide temperature range, it is important to understand the variation of resistivity with temperature. In Fig. 5, the resistivity of undoped, lightly doped, and degenerately doped n-type β-SiC is plotted as a function of temperature for the calculation of the TCR, which is defined as

\[
TCR = \left\{ \frac{R(T) - R(T_{ref})}{R(T_{ref})} \right\} \frac{T - T_{ref}}{T_{ref}}.
\]

The TCR reflects both the magnitude and direction of the dependence of resistivity on temperature. Both the undoped and lightly nitrogen-doped samples have a negative TCR at low temperatures, representing a decrease in resistance with temperature. At higher temperatures, the TCR becomes positive and the resistance increases with temperature. The undoped samples exhibit a positive TCR above -50°C and above room temperature the TCR has an approximately constant value of 0.72% /°C. These characteristics are very similar to those exhibited by silicon samples of similar resistivity. The nitrogen-doped samples are less temperature-dependent than the undoped ones and have a positive TCR only above 200°C, at which point the resistance increases in a nonlinear manner. The lowest TCR is exhibited by the degenerately doped gauges, which have a positive TCR of 0.04% /°C at all temperatures measured.

In general, at low temperatures (typically < 0°C), the resistivity of extrinsic semiconductors decreases with increasing temperatures due to the ionization of impurities. In this regime, the dominant scattering mechanism, impurity scattering, bears a smaller effect on the resistivity than the carrier generation does. Once the impurities are fully ionized, usually at \( T = 0°C \), the resistivity increases due to lattice scattering, which is a larger effect than the thermal electron-hole generation. At high temperatures, the impurity carriers are swamped by intrinsic carriers, causing the resistivity to decrease once again. This type of behavior is exhibited by β-SiC, as shown in Fig. 5. However, the undoped samples appear fully ionized at a much lower temperature than the lightly nitrogen doped samples. This effect may be explained by the donor mechanisms that control the electrical properties of β-SiC grown on silicon. Photoluminescence measurements [16] have determined that in the nitrogen-doped films, nitrogen is a substitutional donor with an activation energy of 40–54 meV, depending on the doping level. However, in the undoped films the principal donor, which has an activation energy of 18 meV, is not substitutional nitrogen [16]. At this time, the cause of this shallow donor is unknown. Nevertheless, it is possible, that the 18-meV donor, because of its lower activation energy, causes a lower ionization temperature in the undoped samples.
In the case of degenerately doped SiC (10^{20} \text{ cm}^{-3}), the Fermi level is in the conduction band. Thus the carriers are fully ionized at all temperatures and the TCR increases with temperature due to scattering effects.

Intrinsic carrier generation was not observed in the TCR of SiC up to 800°C, because of the material’s wide bandgap. As with silicon, the TCR of SiC decreases as the carrier concentration is increased. This is due to the effects of statistical degeneracy, which make semiconductors behave more like metals, having lower TCR’s.

VII. TEMPERATURE COMPENSATION

In a pressure or strain transducer, it is important to have an output which is independent of temperature. Simple circuit compensation techniques have been applied to silicon sensors to compensate for the effects of TCR and TCGF [17]. However, for these techniques to be valid, the following conditions must be met:

1) TCR is positive, preferably constant,
2) TCGF is negative,
3) |TCR| > |TCGF|.

In order to demonstrate pressure measurement, two Fig. 1(a) type n-SiC strain gauges (0.7 \Omega \cdot \text{cm}) were glassed onto a circular steel diaphragm (diameter = 0.75 in, thickness = 0.044 in), which was packaged in a pressure vessel. One gauge was placed near the edge of the diaphragm, while the other was placed in the center. When the diaphragm was subject to a uniform overhead pressure, it deflected downwards, causing the gauges at the edge and the center to be in tension and compression respectively (Fig. 6). The gauges were placed into a Wheatstone half bridge, so that a linear voltage output could be achieved with pressure.

The pressure transducer was tested at temperatures up to 350°C at pressures between 10–310 psi. Fig. 7(a) shows the output versus pressure for different temperature ranges, while in Fig. 7(b), the output is plotted against temperature at a constant pressure of 210 psi. The output increases linearly (within 2%) with pressure and decreases with temperature. This output decrease begins to level off near 300°C, while at 350°C, it is almost completely constant with temperature at approximately half of the room-temperature sensitivity. This supports the data of Fig. 4, which indicate that the temperature dependence of the gauge factor is significantly reduced above 300°C. The change in sensitivity with temperature is due primarily to the gauge factor, but is also affected by a 10% decrease in the Young’s modulus of the diaphragm over the temperature range which causes a slight increase in output. It is also likely that the shear strength of the mounting agent decreases with temperature, and thus the strain is not as effectively transmitted from the force collector to the gauges at elevated temperatures.

While the device of Fig. 7 shows simple pressure measurements, a highly accurate and durable transducer necessitates the fabrication of an integrated force collector/sensing network structure. In a related study [18], [19], the authors have developed photoelectrochemical processes to micromachine sensor structures in SiC. Micromachining of structures, such as diaphragms and beams in β-SiC on Si has also been accomplished by Tong et al. [20].

IX. CONCLUSION

The data in this paper have clearly demonstrated that n-type β-SiC is a potentially useful material for piezo-
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REFERENCES


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