Wireless battery-free SiC sensors operating in harsh environments using resonant inductive coupling

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Abstract—Silicon carbide (SiC) has been extensively investigated in the last decade, specifically for applications in harsh environments. However, most SiC sensors require an external power supply which cannot operate at high temperatures. This work develops a new sensing technology in a SiC platform based on near field communication to eliminate the requirement for wired power sources. 3C-SiC temperature sensors were fabricated from a SiC-on-insulator substrate formed by anodic bonding. The sensors functioned based on the thermoresistance of the SiC films with the high TCR of -13,000 ppm/K at 300 K and -3,000 ppm/K at 600 K. The change in the resistance of the SiC sensors was wirelessly measured using a reading coil placed outside of the heating chamber, showing a significant shift in the resonant frequency (-400 ppm/K at 600 K) of the coupling-impedance under the variation of temperatures. The proposed technique is promising for the development of wireless wide-band-gap sensors used in extreme conditions.

Index Terms—SiC, wireless sensors, harsh environments

I. INTRODUCTION

Harsh environments are abundant in multi-trillion dollar industries, including automobile, gas/oil transportation, mining, and space/deep-sea exploration [1], [2]. The extreme conditions generally reduce the life-time of devices, and could result in catastrophic failures. To avoid system failures and improve operational safety, there is a need for long-term and high accuracy monitoring of the systems [3]–[5]. Micro Electro Mechanical Systems (MEMS) have been emerging as a promising approach to provide real time, low cost, and reliable solutions for structural health monitoring [6], [7]. Nevertheless, the use of silicon-based MEMS sensors in harsh environment is questionable due to its low energy band gap, inferior wear-resistance, and high oxidation rate.

Due to the limitation of silicon (Si), silicon carbide (SiC) has attracted great deal of attention as a superior material for operation in harsh environments [8]–[11]. The wide band gap of SiC enables high temperature (above 300°C) operation of SiC-based electronic devices, such as diodes and transistors [12]–[14]. The strong mechanical properties in SiC have also been utilized to improve the wear-resistance of devices which are coated with a thin layer of SiC [15]. To date, there

Fig. 1. Concept of battery-free, wireless SiC sensors where the sensors are embedded inside high temperature and mechanical/chemical corrosive environments, while the readout circuits can be placed outside.

have been a large number of SiC sensing devices developed, including temperature, pressure, and gas sensors [16]–[20]. However, since most SiC sensors require a power supply for operation, there is a need for a power source that tolerates the same harsh environment conditions unless the device is wirelessly powered. Yang *et al.* reported a wireless sensing technology, where 4H-SiC JFET and varactors were employed to develop an oscillating circuit, which could emit RF signals for wireless communication [21]. However, a source functioning in harsh environments was required to power the circuit for RF communication.

This paper presents battery-free and wireless SiC-on-insulator temperature sensors employing the near field communication technology. The key concept of the proposed sensing technique is that the sensor output can be measured using an external coil placed outside of the high temperature zone through resonant inductive coupling, eliminating the requirement for an internal power source, Fig. 1. The coupling inductor can then be connected to a power supply that is maintained at acceptable environmental conditions. This technology could open a pathway towards the development of wireless SiC sensor-networks operating in harsh environments.

II. RESULTS AND DISCUSSION

SiC temperature sensors were fabricated from 300 nm crystalline SiC on glass wafers. The wafers were formed using anodic bonding to transfer a lightly doped SiC thin film (with a carrier concentration of $N_D \approx 10^{16} \text{ cm}^{-3}$) from Si to a glass substrate following by Si removal, Fig. 2(a). [22] Ni/Al was deposited and patterned on the transferred films to form SiC resistors with different resistances, Fig. 2(b). The Ohmic contact was made between metal lines and SiC and was confirmed to be operational at temperatures up to 600K, Fig. 2(c). Figure 2(d) shows the equivalent circuitry for the wireless communication in which a commercial coil ($L = 7 \mu\text{H}$) and a high temperature ceramic capacitance ($C = 470 \text{ pF}$) were combined with the as-fabricated SiC resistor (i.e.

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Fig. 2. (a) Fabrication flow; (b) Microscopic photograph of the devices; (c) I-V curve of SiC resistors; (d) Equivalent circuit for wireless communication.

the temperature sensor) to form an LCR circuit placed inside a temperature chamber (LinkamTM). In the readout circuit, another coil placed outside of the chamber was used to generate and receive AC signals when coupling with the LCR circuit. The change in the coupled resonant frequency was measured using a network analyzer. Since the temperature outside of the chamber was significantly lower than that inside, the change in the inductance of the reading copper coil due to temperature variation is negligible.

Prior to characterizing wireless communication in SiC sensors, we investigated the thermoresistance of the as-fabricated devices by increasing the temperature from 300 K to 600 K with an incremental step of 30 K. Evidently, the resistance of the lightly doped SiC samples decreased significantly with increasing temperatures, Fig. 3. The resistance of the SiC sensor was stable when the temperature was maintained at a constant set point. The temperature coefficients of resistance ($TCR = (\delta R/R)/\delta T$) was found to be -13,000 ppm/K at 300 K and decreased to -3000 ppm/K at 600 K. This large negative TCR was resulted from the inactive dopants in the (111) SiC samples: the impurities in the lightly doped SiC were activated and became conductive upon receiving sufficiently high thermal energy: $\sigma \approx \exp(-E_a/k_B T)$, where σ is the electrical conductance of SiC; E_a is the activation energy; and k_B is the Boltzmann constant [23]. The decrease in the TCR at high temperature is considered to be due to the saturation of the charge carriers at elevated temperatures. This property indicates that for wireless communication sensors, the coupled resonant frequency could exhibit a large shift at low temperature and smaller shift at higher temperatures.

We investigated the wireless temperature measurement by placing the SiC sensors on the Linkam thermal chuck and covered the chamber using a glass slide of 1.2mm thickness. The reading coil was placed outside of the chamber and connected to the network analyzer. When an AC signal was sent to the reading coil, the resulting magnetic field induced a current into the LCR circuit of the SiC temperature sensors, which in turn resulted in a voltage in the reading coil, following the Faraday's law. The frequency dependence of the impedance of the reading coil is given by [24], [25]:

$$Z(e) = R_r + j\omega L_r + \frac{\omega^2 M^2}{R_s + j\omega L_s + \frac{1}{j\omega C_s}} \quad (1)$$

where ω is the sweeping frequency while M is the mutual

Fig. 3. Thermoresistive effect of the SiC-on-glass temperature sensors.

inductance between the two coils. Accordingly, the resistance change of the SiC sensors due to temperature variations results in a change in the impedance of the external circuit, leading to a shift in the resonant frequency of the impedance-phase:

$$\angle Z(e) = 90 - \arctan\left(\frac{\text{Im}(Z(e))}{\text{Re}(Z(e))}\right) \quad (2)$$

Since the SiC temperature sensor exhibits a negative TCR, the resonant inductive coupling frequency is expected to red shift when increasing the temperature.

The wireless temperature measurement was performed on three SiC sensors with resistances varying from 60 Ω to 180 Ω , initially at room temperature. The inductive impedance was calculated based on the S_{11} parameters obtained from the network analyzer (the reflection mode). Figure 4 shows the phase of the three resistances with the frequency swept from 0.75 MHz to 5 MHz. At room temperature, the three sensors (with resistances of 60 Ω , 90 Ω , and 180 Ω) show three particular resonant peaks at 1.5 MHz, 2.13 MHz, and 3.31 MHz, respectively. The experimental result showing the drop in resonant frequency with decreasing resistance of the sensors was in solid agreement with the theoretical model of Eq. 2. Additionally, increasing the resistance of the SiC sensors resulted in a decrease in the Q-factor ($Q \equiv (1/R_s) \times \sqrt{L_s/C_s}$), which makes it challenging to detect the frequency. To overcome this, the resistance of the sensors was designed to be below 200 Ω to ease the measurement of resonant frequency. Furthermore, the frequency used in this study falls within the high frequency (HF) range owing to its advantage over low frequencies (e.g. relevant to small inductance and capacitance circuits, and higher sampling rate), as well as the very high frequencies (e.g. less sensitive to the RF interference).

Fig. 4. The resonant inductive coupled phase of SiC sensors with different resistances. Larger resistances show lower Q and larger resonant frequency.

Fig. 5. Wireless SiC sensors characterized at high temperatures. (a) The phase of the coupling impedance ($R = 180\Omega$); (b) Relationship between resonant frequency and temperatures; (c) A comparison of the frequency-shift in SiC sensors with different resistances; (d) Characterization of the SiC films in several chemically corrosive solutions; (e) Oxidation test of SiC compared to Si counterpart (Inset: Raman spectra of SiC); (f) I-V curve of the oxidized SiC and Si.

Figure 5(a) shows the resonant inductive coupling phase of the 180Ω sensor measured using the reading coil when increasing the temperature from 300 K up to 600 K. Evidently, the coupling resonant frequency decreased (i.e. red shifted) when the temperature was increased. In addition, the Q factor of the sensors at low temperature ($Q < 0.5$ at $T = 300$ K) was much lower than that at high temperature ($Q = 4$ at $T = 600$ K). This trend is consistent with the theoretical analysis as the smaller resistance in the LCR circuit of the sensors will lead to a higher Q factor. We employed the high-degree polynomial fit function to estimate the resonant frequency, Fig. 5(a) inset. The left-shift in the resonant frequency was much larger at a low temperature range (the relative frequency shift $(\delta f/f)/\delta T = -9,500$ ppm/K at $T = 273$ K), and decreased at high temperature ($(\delta f/f)/\delta T = -400$ ppm/K at $T = 600$ K), Fig. 5(b). This result agrees with the TCR measurement data that the 3C-SiC resistances significantly changes at low temperatures, and had less variation at higher temperatures. We compared the frequency shift of the three sensors (with resistances at 300 K being 60Ω , 90Ω , and 180Ω). Figure 5(c) shows that at high temperatures ranging from 450 K to 600 K, the sensors with a larger resistance offered better temperature sensitivity. Nevertheless, as discussed above, large resistances at room temperature also leads to a very small Q-factor, making measuring the resonant frequency challenging. Using an array of sensors with different resistances is recommended to enable a wide range of temperature measurement.

To further demonstrate the capability of the SiC sensors, we investigated the tolerance of this sensing platform to corrosive and wet oxidation conditions. The as-grown SiC film and a bulk Si sample were immersed into different solutions such as TMAH, KOH, and HNA at 363 K for the corrosive test. The Si samples were rapidly attacked by these solutions, showing a significant change in the surface roughness, Fig. 5(d). A 300 nm-thick Si film of an SOI wafer was completely disappeared after 10 minutes. On the other hand, the thickness and the

surface morphology of the SiC film remained unchanged under the similar conditions after 24 hours, Fig 5(d). The oxidation test was then performed on a patterned SiC-on-Si sample to compare the tolerance of the two materials. After being inserted into a wet oxidation chamber at 1200 K for 2 hours, the Si layer was markedly oxidized and turned into silicon oxide, while no significant change was observed in SiC, which can be colorimetrically visualized by either naked eyes or optical microscope, Fig. 5(e). We then deposited Al on the surface of SiC and Si and measured their electrical conductance. Figure 5(f) shows the I-V curves of the oxidized SiC and Si films, indicating that while the SiC films exhibited stable electrical conductance after high temperature oxidation, the Si sample was completely blocked by a thick layer of oxide formed on its surface. These results indicate that cubic SiC-based sensors could outperform the conventional Si-based counterparts in highly corrosive and oxidation environments. The robustness of SiC subjected to 1200 K also proves the feasibility of our sensors for high temperature wireless sensing applications. In the present work, we employed commercial components such as inductance and ceramic capacitance which only work below 600 K, the wireless sensing experiment was limited to this temperature. However, these components can be replaced by highly doped SiC inductance and SiC-based capacitors, which could enable the sensors to function at much high temperatures where Si cannot be used. This work will be carried out in a future study.

III. CONCLUSION

We developed a SiC wireless sensor employing the resonant inductive resonant phenomenon. Owing to its superior physical strength, SiC sensors can be used in high-temperature and high-corrosive environments. When coupled with wireless power transmission and readout, SiC sensors enable the measurement of different physical parameters under hostile

conditions. As a proof of the concept, we demonstrated SiC-on-insulator sensors which can detect temperatures ranging from 300 K to 600 K based on the coupled resonant frequency.

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