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Development of High Temperature Wireless Sensor Technology Based on Silicon Carbide Electronics

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Smart Sensor Systems that can operate at high temperatures are required for a range of aerospace applications including propulsion systems. This paper discusses the development of a high temperature wireless system that includes a sensor, electronics, wireless communication, and power. In particular, a wireless pressure sensor was demonstrated at 300°C, with signal transmission over one meter distance and power partially derived from scavenged energy. The circuit had a nominal oscillation frequency of near 100 MHz and used a commercial SiC metal semiconductor field effect transistor (MESFET) together with metal-insulator-metal (MIM) capacitors and a thin film inductor/antenna. With the sensor and oscillator circuit at temperatures from 25 to 300°C, the oscillator frequency, detected at a distance of one meter, was found to vary repeatably as a function of pressure. This work is considered a foundation for the development of higher temperature Smart Sensor Systems for use in harsh environments.

Introduction

Smart Sensor Systems that can operate at high temperatures are required for a range of aerospace applications (1-2). For example, for future aerospace propulsion systems to meet the requirements of decreased maintenance, improved performance, and increased safety, the inclusion of intelligence into the propulsion system design and operation is necessary. These propulsion systems must incorporate technology that will monitor propulsion component conditions, analyze the incoming data, and modify operating parameters to optimize propulsion system operations. This implies the development of sensor systems that will be able to operate under the harsh environments present in an engine. Likewise, applications such as Venus exploration missions require systems that can operate in the harsh environments present on the Venus planetary surface (3-4).

Further, for almost every sensor or electronic processing unit going into an engine to improve the *in-situ* monitoring of the components, communication and power wires follow (5). The wires may be within or between components, or from the engine to the controller/power source. More sensor systems added to the aircraft increases the number of wires and the associated weight, complexity, and potential for failure. The burden imposed by wires associated with sensor implementation has limited sensor use and engine self-monitoring capabilities. Thus, there is a need for high temperature sensors and electronics, but also for high temperature wireless technology. This implies the integration of sensors, electronics, wireless circuits, and power into a single system.

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A goal of the research at NASA Glenn Reseach Center (GRC) is to enable intelligent vehicle systems by developing Smart Sensor Systems including sensors, electronics, communication, and power that is operational in harsh environments including engine applications. However, given the harsh environments inherent in propulsion systems, the development of engine-compatible electronics for engine applications is not straightforward. The use of sensors and complex electronics in these environments implies operation at temperatures above 300°C. To be useful, such electronics need to be as small, lightweight, and non-intrusive as possible; in addition, these electronics should preferably operate without thermal management overhead in hot regions, at or near very hot combustion chambers and exhaust gas streams. While silicon-based semiconductors have enabled quite complex, room-temperature circuits to be miniaturized onto small chips, the extension of this technology to temperatures above 300°C appears impractical (6,7).

In contrast, wide-bandgap silicon carbide (SiC) presently appears to be the strongest candidate semiconductor for implementing 400-600°C integrated electronics, as other high temperature electronics materials are either physically incapable of functioning at these high temperatures (silicon and silicon-on-insulator), or are less-developed (GaN, diamond, etc.) (6-7). Single-crystal wafers of either the 6H or 4H crystal structures of SiC are commercially available with sufficient quality and size to enable foundry mass-fabrication of discrete devices and integrated circuits. Operation at 500°C has been demonstrated for thousands of hours; these time frames are now viable for implementation to engine conditions for extended periods (8-10). This is a notable advancement in high temperature electronics and would allow high temperature signal processing at temperatures far beyond that capable in silicon electronics. However, a range of other components and further technology development are necessary to produce a high temperature, stand-alone Smart Sensor System that includes communication.

This paper discusses the development of a high temperature wireless system that includes a sensor, electronics, wireless communication, and power. While the overall objective is 500°C operation, in order to demonstrate the concept and explore the maturity of component technologies, demonstration of these capabilities at 300°C has occurred. A wireless pressure sensor was demonstrated at 300°C with signal transmission over 1 meter (m) distance and using power derived, in part, from scavenged energy. This paper describes this 300°C high temperature wireless system demonstration. In particular, this paper will discuss: 1) Previous activities in the field of high temperature wireless; 2) An overview of the approach involved in this high temperature wireless system demonstration; 3) Results of wireless sensor system testing; and 4) Discussion of implications of this work and future plans. It is concluded that this work is a foundation for the development of higher temperature Smart Sensor Systems for use in harsh environments.

High Temperature Wireless Background

A range of different approaches can be considered for high temperature wireless systems (11). Approaches include either passive wireless communication without signal processing (12-15), or operation at lower temperatures such as 300°C where silicon on insulator technology is viable (16). While these approaches can provide communication with sensor systems, the ability to both signal process and communicate at higher temperatures than 300 °C is limited. As noted above, the use of SiC semiconductor electron-

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ics is a viable approach towards operation of a high temperature (> 300 °C) wireless system that includes signal processing. However, in order to create a SiC-based high temperature wireless circuit, it is necessary to integrate the SiC electronics with high temperature passive devices and interconnections. A simple and robust wireless sensor system employs a local oscillator, the frequency of which is modulated as a function of the sensed parameter. Integration of passive components with a commercially available SiC metal semiconductor field effect transistor (MESFET) has been performed in previous research to demonstrate the ability to design the circuit, the operability of the passive components, and the integration of the components with a SiC transistor.

For example, a 1 GHz oscillator and a 1 GHz active transmitter (oscillator and antenna) operating at 200ºC (17) and 270ºC (18) have been demonstrated. These circuits used chip capacitors and SiC MESFETs mounted onto the carrier. The temperature characteristics of the SiC MESFET were measured and used with temperature-dependent characteristics of the passive components to design the oscillator. The first design was a differential oscillator that operated at 475˚C with an output frequency of 453 MHz into a non-50 Ω load. A disadvantage of this circuit was the sensitivity of the frequency to temperature dependent changes in the transistor capacitance. A second circuit, a Clapp Oscillator that has less dependence on the transistor capacitance, was built and is shown in Figure 1. Testing showed that it operates at 1 GHz into a 50 Ω load over the temperature range of 30 to 200˚C. Modeling predicted that the circuit should have operated through 300˚C, but increased loss in the passive devices limited the operation.

This oscillator was a proof-of-concept device to show the viability of the design approach. It also showed that greater gain was required from the transistors if they were to operate at 1 GHz and temperatures above 300˚C. Moreover, it is noted that the characteristics of the commercial transistor, which was not designed for use at this high temperature, varied over time at high temperature. A critical aspect of oscillator performance is noise generation by the circuit because noise will limit the data rate of the wireless system. While the literature indicates that further research on noise performance of SiC transistors is required, preliminary studies show that low frequency noise of SiC transistors initially increases with increasing temperature, but after a maximum is reached, the noise spectral density decreases with temperature. Therefore, noise performance of SiC transistors does not appear to be a limiting factor in overall device performance (19).

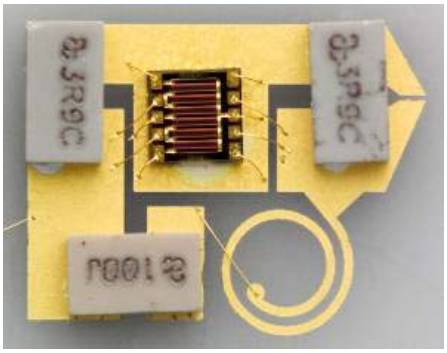

Figure 1. Photograph of oscillator comprised of SiC MESFET, ceramic chip capacitors, a spiral inductor, and gold wire bond interconnects. The dimensions of this unit are 4.3 by 4.9 mm.

Wireless pressure sensors operating at 400ºC and 20 MHz (20), as well as 270ºC (21), have been demonstrated. This work included the integration of a Cree SiC MESFET with passive components for measurement of pressure with wireless transmission. In particular, the wireless transmission of sensor data at 400˚C at 31.5 MHz for limited times using

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commercial SiC parts was demonstrated (20). Although the SiC MESFET was operating at a carrier temperature of 400ºC, the capacitors and resistors were probably operating at a lower temperature; these were chip level components mounted normal to the substrate with an expected temperature gradient. Although an excellent step forward, the system had limited power transmission, dynamic range, communication distance, and was not a complete integrated system with power.

Thus, there are notable technological challenges related to advancing from previous work towards the development of an integrated Smart Sensor System with sensor, signal conditioning, communication, and power operational at a target temperature of 500ºC. Ideally, such a high temperature Smart Sensor system would be self-contained and able to be placed wherever needed without rewiring, e.g., a high temperature analog to the "Lick and Stick" Smart Sensor System under development for near-ambient temperature applications (2). However, in order to reach such an objective, an understanding of the basic component technologies is needed combined with the maturation of these technologies for 500ºC operation. Part of this development process is the demonstration of the various component parts at lower temperatures to prepare for 500ºC operation.

Demonstration Approach: Components and System Integration

The objective of the demonstration described in this paper is to prepare for future 500˚C wireless sensor system operation by investigating system component operation at 300˚C. This lower temperature is considered the borderline at which a number of conventional component parts begin to become inoperative. For example, silicon-based electronics are typically considered to have an upper temperature limit of 300˚C (6). Operation at 300˚C is considered a proving ground for system approaches and integration needed for 500°C operation. It also allows for characterization and benchmarking of sensor systems operable at 300°C in order to identify technology areas to focus on for 500°C operation. The overall approach for this demonstration is to use existing technologies at 300˚C if viable, and develop new technologies if existing technologies do not meet the needs of the application.

Multiple fields of expertise in high temperature technology must be brought together to integrate the various subsystems necessary for this demonstration. These include: a pressure sensor, power supply, SiC wireless circuit, and system integration into a testing system. The following subsections will describe each subsystem and the rationale for this approach.

Pressure Sensor

Capacitive sensor systems have significant advantages for wireless circuits. In oscillating circuits based on inductors and capacitors (LC), changes in capacitance more readily affects the resonant frequency than changes in resistance. While NASA GRC has a long standing effort in pressure sensors based on resistance changes (22), capacitive pressure sensor development is still at an early stage. Thus, a commercial pressure sensor was chosen for this demonstration (23). This capacitive pressure sensor is silicon based with an expected maximum operation temperature of 300°C. Bare starting sensor die as shown in Figure 2 were used and combined with high temperature packaging techniques such as those described in reference 24, to prepare the pressure sensor for system demonstration.

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Characterization of the basic properties of the packaged pressure sensor was conducted from room temperature to 300°C. A subset of the characterization results is shown in Figure 3: the response of the sensor to pressure cycles from 0 to 100 psi and back to 0 was measured at temperatures from 25°C to 300°C and back down to 25°C. While some variation in the sensor response was noted, these tests did show the capability of the basic sensor, coupled with high temperature packaging, to be able to function up to 300°C.

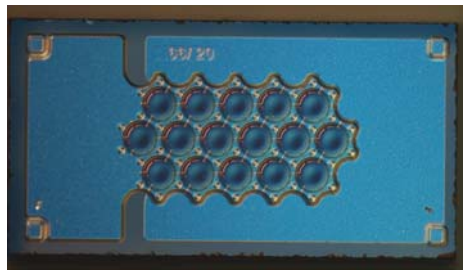

Figure 2. Magnified view of the microFAB Capacitive Pressure Sensor. Shown are sixteen 60-micron diaphragms.

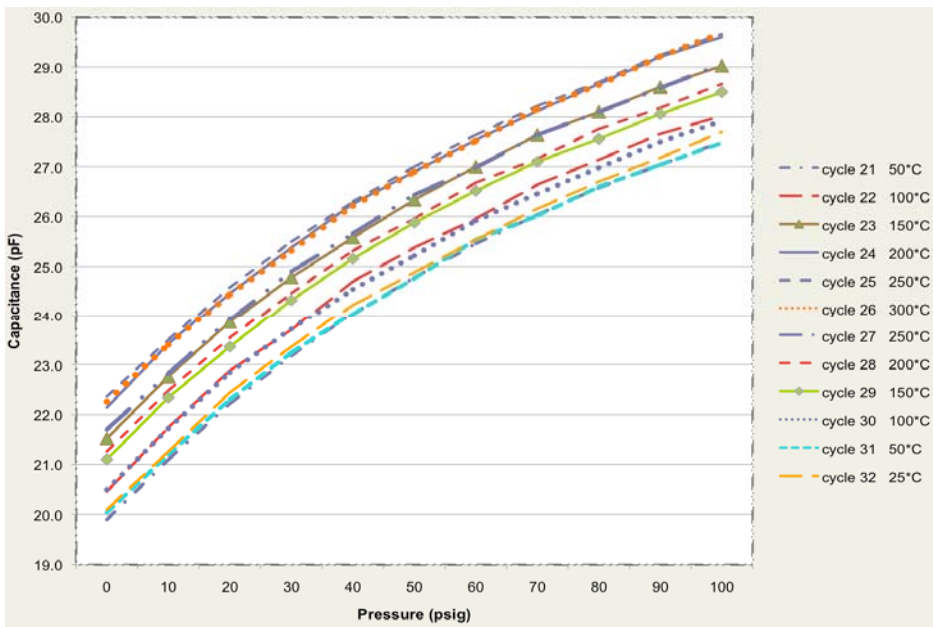

Figure 3. Capacitance versus pressure of the capacitive pressure sensor in characterization testing over multiple cycles. Results show the basic capability of the system to operate at 300°C.

Power Supply

In order to provide power to a sensor system *in-situ* without external power wires, one option is a battery. While high temperature batteries exist (4,25) and can provide power at 500°C for some applications, their present size may limit use in high-temperature applications such as an engine. Rather, power scavenging using thermoelectrics or piezoelectrics (26-27) that take advantage of the considerable amount of energy already present within the engine has notable appeal. In particular, NASA GRC has led development of a range of relevant thermoelectric based technologies from thin film thermo-piles for heat flux sensors (28-29) to environmentally durable silicide based thermoelectric materials for 500 C operation (30-31).

However, these material systems are not fully developed to completely provide *in-situ* power for system operation. For the purposes of showing the proof-of-concept of power scavenging for high temperature operation at 300 C, a commercial thermoelectric module was used (32). These thermoelectric power units are encapsulated to decrease degradation

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and operate for limited times at 300°C. Even with several hundred degrees of thermal gradient, each thermocouple within a module provides a limited voltage and requires a series connection of many thermocouples within a module to achieve several volts.

Power scavenging was performed by providing a near 300°C gradient across several thermoelectric modules as shown in Figure 4a with the hot side exposed to 300°C, while the other side of the unit was cooled with the heatsink chiller. The voltage produced by the power scavenging was combined with power provided by a standard power supply as shown in Figure 4b. The coupled power supply system of scavenged and traditional power provides overall power to operate the pressure sensor and SiC MESFET/wireless circuit.

a) b)

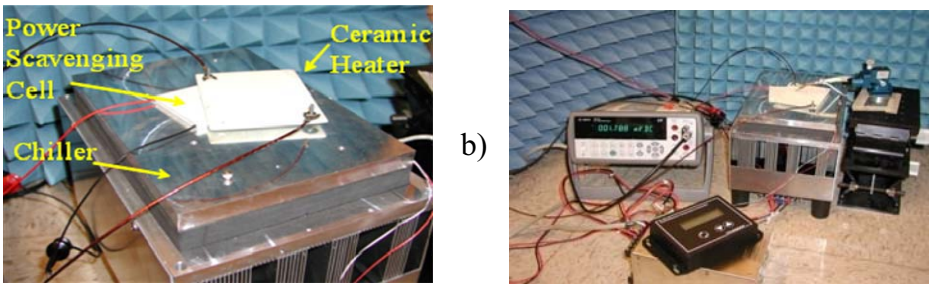

Figure 4. Power Supply System. a) Power scavenging unit composed of thermoelectric materials exposed to a temperature gradient provide by a ceramic heater and chiller. b) Power scavenging unit combined with a standard power supply to provide overall power for the sensor/SiC MESFET/wireless circuit.

SiC-Based Wireless Circuit

As described above, existing NASA GRC circuits based on SiC JFETs, have shown world record durability at 500°C. However, at this stage of SiC JFET development at NASA GRC, an LC oscillator employing one of our 500°C JFETs would operate at relatively low frequencies (possibly on the order of MHz or less). One approach to providing higher frequency operation is the use of a commercial MESFET. A Cree SiC MESFET (33) was chosen as the core SiC circuit for this demonstration (Figure 5a). Although limited in durability at higher temperatures, this MESFET is operational at 300°C and allows a wider frequency range in wireless circuit design than other SiC-based devices.

The SiC MESFET was integrated with the capacitive pressure sensor described above into a wireless sensor system as shown in Figure 5. This system integrated a sensor, the SiC MESFET, capacitors, and an spiral antenna/inductor onto a single substrate to form a High Temperature Wireless Pressure Sensor System. The complete system was fabricated on an alumina substrate using thin film processing techniques. A more detailed description of the overall approach to this wireless pressure sensor system is described elsewhere (34). It should be noted that a major advancement related to the High Temperature Wireless Pressure Sensor System is the level of thin film technology integrated into the system. This includes the development and characterization of thin film components such as Metal-Insulator-Metal (MIM) capacitors and thin film spiral inductors. In contrast to Figure 1, these passive devices do not protrude from the surface of the device. The ability to form thin film versions of these components is a major step towards fabricating integrated sensor systems of minimal size, mass, and power, as well as providing systems with minimal thermal gradients and more uniform performance.

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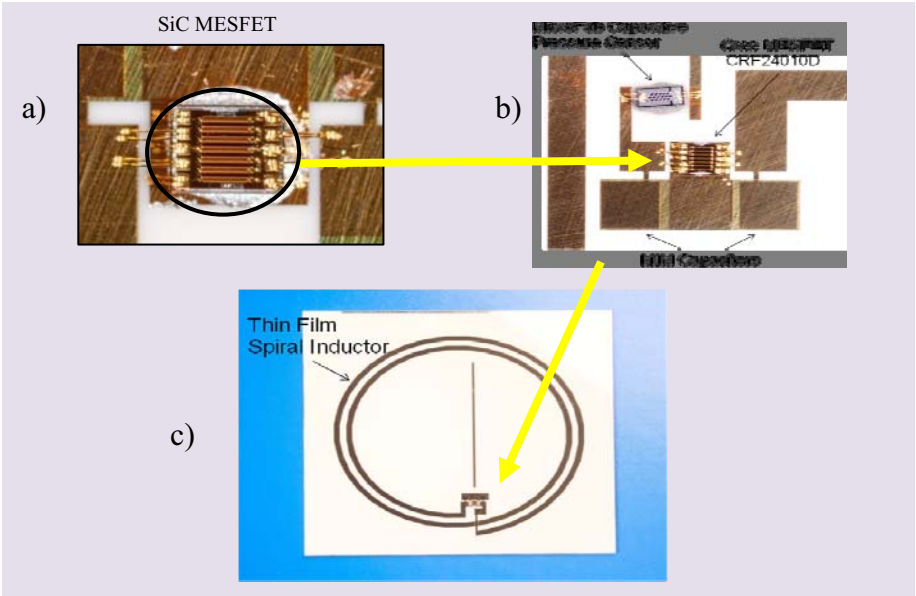

Figure 5. Assembly approach for 300°C High Temperature Wireless Pressure Sensor System. (a) A SiC MESFET. (b) This MESFET is integrated on an alumina substrate with a capacitive pressure sensor, thin film capacitors, and spiral inductor/antenna. (c) The complete system is on a single alumina substrate with a minimal amount of protruding subcomponents. The alumina wafer 50.8 by 50.8 mm and the spiral inductor has an inner radius of 17 mm.

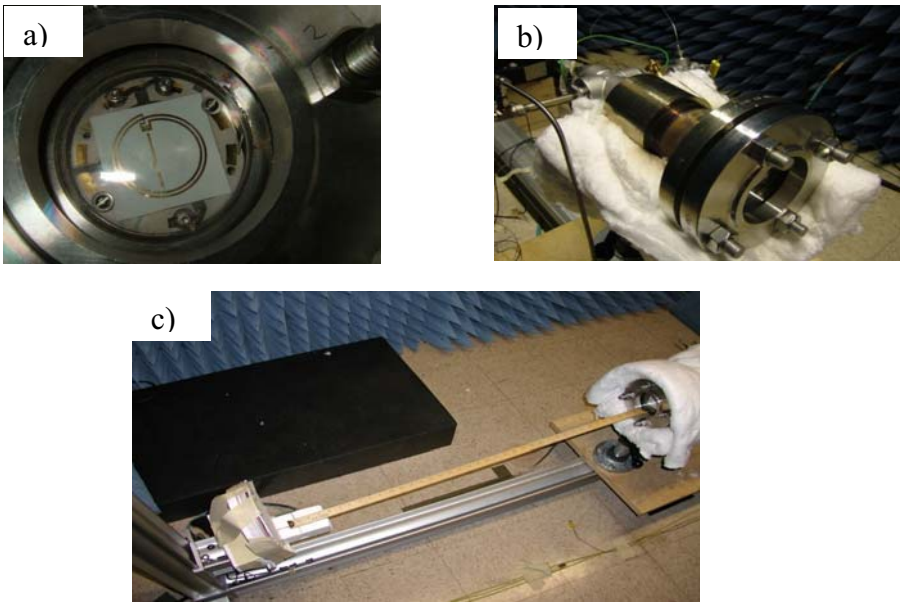

Figure 6. Test Chamber Assembly. a) High Temperature Wireless Pressure Sensor System mounted in pressure chamber. b) Pressure chamber and insulation. c) Pressure chamber with sending antenna at 300°C and receiving antenna at room temperature.

System Integration and Test Chamber

In order to demonstrate the wireless transmission of data associated with this SiC based sensor system at temperature and at various pressures, a high temperature pressure

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vessel was designed. This system allowed the High Temperature Wireless Pressure Sensor System described above to transmit over a 1 meter distance while under various pressures, and temperatures ranging from 25°C to 300°C. Figure 6 shows the overall testing system structure. In particular, the High Temperature Wireless Pressure Sensor System shown in Figure 5 is placed in a pressurized stainless steel chamber (Figure 6a). The chamber is fitted with a quartz window that allows wireless transmission of the data from within the chamber to an external receiver. The overall pressurized chamber is enclosed in insulation and heated to temperatures ranging from 25°C to 300°C (Figure 6b). The interior of the chamber can be pressurized at a constant value from 0 to 45 psi. The system receives power, including the scavenged power from the unit described in Figure 3, from wires fed into the pressure chamber. Data is transmitted from within the pressure chamber to a receiving antenna at room temperature approximately 1 meter away. Thus, this testing system is meant to demonstrate the various system components of a High Temperature Wireless Pressure Sensor System with power scavenging at temperatures ranging from 25°C to 300°C with pressures ranging from 0 to 45 psi.

Test Results

The High Temperature Wireless Pressure Sensor System was tested in the test chamber described above. The circuit had a nominal oscillation frequency of near 100 MHz, and nearly 5.7 V was consistently provided by the power scavenging thermoelectric unit. With the sensor and oscillator circuit at temperatures ranging from 25 to 300°C, the oscillator frequency was found to vary repeatably as a function of pressure. Figure 7 shows the sensor response to pressures of 0, 25, and 45 psi at 300°C. The data is wirelessly transmitted over 1 meter from within the pressure chamber at 300°C to the room temperature receiving antenna. Figure 7 shows the frequency modulated response of the wireless pressure sensor produced at each pressure. The pressure change of 45 psi produces an overall 2.7 MHz shift in oscillator frequency. Both the baseline signal and the shift in the signal are considered significant and readily measurable.

Table 1. The circuit operational parameters at 300°C in the pressure range from 0 to 45 psi including power and current settings to the SiC MESFET, as well as the output frequency and power.

Pressure (psi)	V_{ds} (V)	V_{gs} (V)		V_{gs} Total	I_{ds} (mA)	Frequency (MHz)	Power (dBm)
		Supply	Scavenged				
0	10	1.03	5.7	6.73	80	103.93	-17.7
15	10	1.05	5.71	6.76	80	103.77	-17.4
25	10	1.07	5.71	6.78	80	102.53	-15.28
35	10	1.12	5.7	6.82	80	101.87	-16.6
45	10	1.12	5.69	6.81	80	101.3	-19.4

Table 1 presents a range of parameters associated with the operation of the SiC MESFET at 300°C from 0 to 45 psi. Included is the pressure, drain-source voltage (V_{ds}), voltage from gate to source (V_{gs}), drain-source current (I_{ds}), frequency, and receive power.

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The I_{ds} was constant across the pressure range. The V_{gs} is supplied in part by the power scavenging circuit which provides near 5.7 V at I_{gs} = 0μA, while the majority of the circuit power (including V_{ds}) is provided by a standard power supply. In summary, this data suggests power scavenging can be used without disruption of overall circuit operation at 300 °C and while maintaining stable operation of the SiC MESFET.

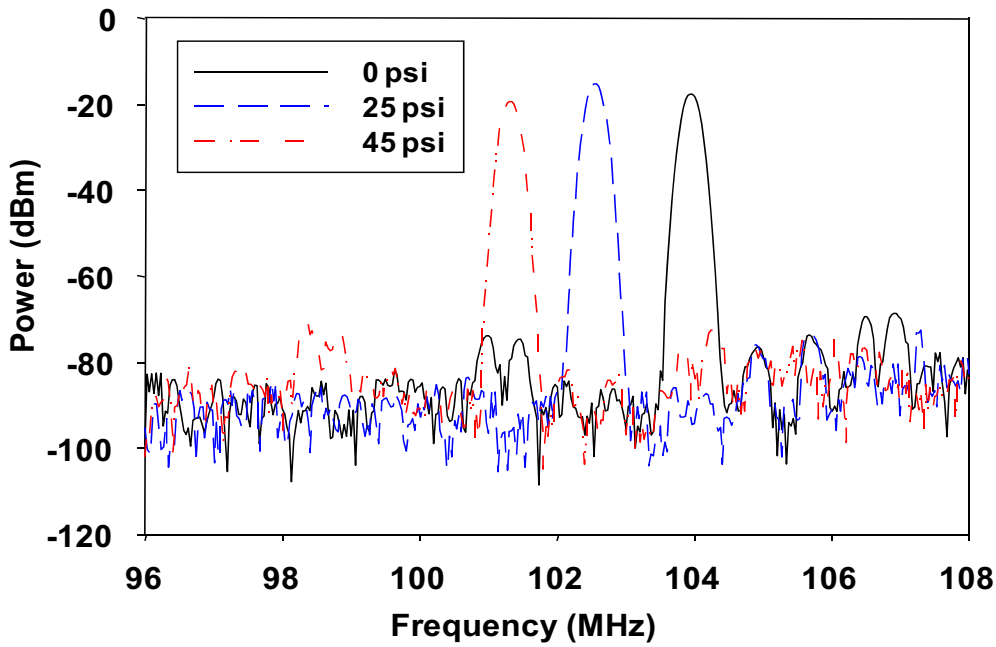

Figure 7. The wireless signal from the High Temperature Wireless Pressure Sensor System operating at 300°C while exposed to top pressures of 0, 25, and 45 psi.

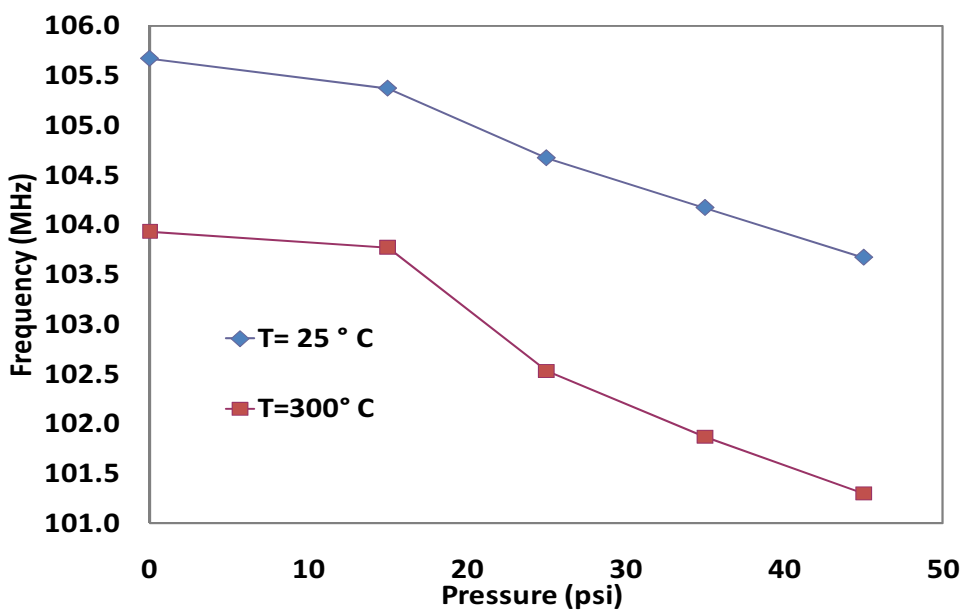

Figure 8. The pressure sensor frequency at 25°C and 300°C at pressures from 0 to 45 psi.

Figure 8 shows a comparison of the oscillator frequency at 25°C and 300°C. These values are taken from received signals such as those in Figure 7 and plotted over the

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range from 0 to 45 psi. The sensor frequency is seen to uniformly decrease with pressure at both temperatures, and the frequency versus pressure curves at the two temperatures are generally parallel. Thus, the basic data from the curves shown in Figure 7 can be used to measure and track the sensor response as a function of pressure. However, independent knowledge of the temperature would be needed for this measurement.

Summary and Conclusions

This paper describes a High Temperature Wireless Pressure Sensor System operational at near 105 MHz and 300°C. The system is composed of a SiC MESFET, capacitive pressure sensor, MIM capacitors, and a thin film spiral inductor/antenna. Operation was demonstrated for temperatures from 25°C to 300°C and pressures from 0 to 45 psi with a resonant frequency shift of about 2 MHz for a 45 psi pressure change. This work also established power scavenging at 300°C to demonstrate self-powering capability to partially bias the gate voltage of the SiC MESFET. Radio Frequency communication at 300°C was demonstrated over 1 m distance to a room temperature receiving antenna.

This work is considered a foundation for the development of higher temperature Smart Sensor Systems for use in harsh environments. During this work, it was found that the operational parameters related to the pressure sensor have a significant impact on overall circuit operation. In particular, internal resistance of the pressure sensor can limit the overall frequency of operation. Significant changes in wireless circuit design were implemented during the course of demonstrating the capability to produce components of a wireless circuit in a thin film form. Finally, this work demonstrates that sensor operation using power scavenging is feasible with proper circuit implementation. However, it is presently unlikely that the operation of a complete wireless system of this type can be performed using power scavenging alone, and the use of another power supply to supplement system power will be necessary awaiting further advances in power scavenging and lower power circuitry operational at high temperature.

These lessons learned will be used in the design of a 500°C High Temperature Wireless Pressure Sensor System presently under development. This includes development of the next generation of SiC electronics circuits specifically designed for this application. The overall approach is to demonstrate the proof-of-concept of a 500°C wireless system including a sensor, signal conditioning, power, and wireless transmission. Operation at this temperature opens a range of application possibilities, from measurement in high temperature engine environments to *in-situ* Venus planetary measurements for the integration of a Smart Sensor System. The work in this paper is a stepping stone to such a technology advancement.

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