

## **An Overview of Wide Bandgap Silicon Carbide Sensors and Electronics Development at NASA Glenn Research Center**

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A brief overview is presented of the sensors and electronics development work ongoing at NASA Glenn Research Center which is intended to meet the needs of future aerospace applications. Three major technology areas are discussed: 1) high temperature SiC electronics, 2) SiC gas sensor technology development, and 3) packaging of harsh environment devices. Highlights of this work include world-record operation of SiC electronic devices including 500°C JFET transistor operation with excellent properties, atomically flat SiC gas sensors integrated with an on-chip temperature detector/heater, and operation of a packaged AC amplifier. A description of the state-of-the-art is given for each topic. It is concluded that significant progress has been made and that given recent advancements the development of high temperature smart sensors is envisioned.

### **Introduction**

Sensors and electronics which can operate at high temperatures are necessary to meet a range of aerospace application needs. For example, in order for future aeronautic propulsion systems to meet the increasing requirements for reduced maintenance and emissions, improved capability, and increased safety, the inclusion of intelligent systems into the propulsion system operation becomes necessary. These propulsion systems will have to incorporate technology that will monitor propulsion component conditions, analyze the incoming data, and modify operating parameters to optimize propulsion system operations (1). Improved intelligence integrated into propulsion systems is also important for Space Exploration applications where improved autonomy is necessary for long duration planetary applications. Propulsion systems that require intense human intervention or monitoring take valuable crew time from other critical functions. Maintenance of such propulsion systems during long-duration missions may not be possible and their failure would endanger both the mission and the safety of the crew. Thus, automated monitoring and maintenance of such propulsion systems, and indeed any high temperature vehicle operating system, would help to enable the NASA Vision for Space Exploration (2). Likewise, operation in such environments as the Venus surface requires sensors and electronics which can operate in the harsh environments. Given the previous lack of electronics that could collect and transmit scientific data in Venus's 450°C lower-atmosphere, almost all proposed missions to explore this important planetary environment were based on very limited mission duration. The ability of a spacecraft (including its electronics and associated sensor systems) to function and return useful data for far longer time periods would greatly improve the scientific return gained from Venus surface missions (3).

Meeting these mission needs implies the development of sensors and electronics, with associated supporting technology such as packaging, which will be able to operate under the relevant operating environments. However, given the harsh environments inherent in applications such as propulsion systems, the development of compatible electronics and sensors is not straightforward. Wide-bandgap silicon carbide (SiC) presently appears to be the strongest candidate semiconductor for implementing 400-600 °C integrated electronics, as high temperature electronics materials are either physically incapable of functioning at these high temperatures (silicon and silicon-on-insulator), or are significantly less-developed (GaN, diamond, etc.) (4,5). 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. SiC devices such as Junction Field Effect Transistors (JFET's) have previously demonstrated reasonable electrical functionality at high temperatures for relatively short time periods. Likewise, a range of sensor technology, including pressure and chemical sensors, can be fabricated using SiC which can perform measurements in harsh environments (6). Besides their inherent strength and durability, fabricating sensors from SiC semiconductors hold the long-term promise of being able to integrate sensors and electronics on the same chip where appropriate.

This paper gives a brief overview of the sensors and electronics development work ongoing at NASA Glenn Research Center (NASA GRC) which is intended to meet the needs of future harsh environment applications. Three major technology areas are discussed: 1) high temperature electronics, 2) sensor technology development including growth of atomically flat SiC materials, and 3) packaging of harsh environment devices and sensors. In each case, the technical challenges are discussed and an example is given which illustrates the existing state-of-the-art. The conclusion summarizes the state-of-the-art as described in this paper and suggests that given recent advancements in core high temperature technology, the development and implementation of high temperature smart sensors is envisioned.

### **High Temperature Electronics**

The use of complex electronics to process, amplify, and wirelessly transmit signals directly from the point of harsh-environment sensing above 300°C would have clear benefits in a variety of aerospace applications. To be useful, such electronics need to be as small, lightweight, and non-intrusive as possible; in addition, it should preferably operate without thermal management overhead in hot regions. While 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 using silicon semiconductors (4,5). The operational lifetime of SiC-based transistors at 400-600°C is not limited by the semiconductor itself, but is instead largely governed by the reliability and stability of various interfaces with the SiC crystal surface. The physical degradation of the metal-semiconductor ohmic contact interface limits the 600 °C operating lifetime of all devices, while high temperature MOSFET (Metal Oxide Semiconductor FET) operating lifetime is also limited by the electrical integrity of the oxide-semiconductor interface. Thus, junction-based transistors without gate insulators appear more feasible in the nearer term. Of the candidate junction-based transistor technologies that might be used to implement SiC integrated circuits, the pn junction gate JFET seems closest to demonstrating long-term operation at 400-600 °C.

An example of the maturity of SiC JFET technology over seven years ago was the demonstration of

600 °C digital logic using SiC JFET's (7). A resistive load Direct-Coupled FET Logic (DCFL) approach was adopted to demonstrate simple 600 °C digital logic using SiC JFET's. A mesa-etched epitaxial gate JFET design was chosen with a two-level interconnect approach using silicon nitride as the dielectric passivation along with oxidation resistant gold for the metal interconnect. However, because non-optimized ohmic contact metals were employed in this experiment, the devices failed after less than an hour of 600 °C operation. Because metal-semiconductor contacts were the primary factor limiting high temperature operational lifetime, focused fundamental research efforts to develop more durable SiC high-temperature ohmic contacts were undertaken. These efforts produced a novel and remarkably durable Ti/TaSi<sub>2</sub>/Pt multilayer contact to n-type SiC that has demonstrated stable ohmic properties over the course of 1000 hours of annealing at 600 °C in air (8). It is important to note that such demonstrated durability in oxidizing air ambient is significant and unique. Almost all other published reports of high temperature contacts study contact durability only in oxygen-free inert-gas or vacuum environments. Durable functionality in oxygen-containing air ambient simplifies high temperature packaging challenges by reducing the need to obtain a perfectly hermetic package seal against oxygen penetration.

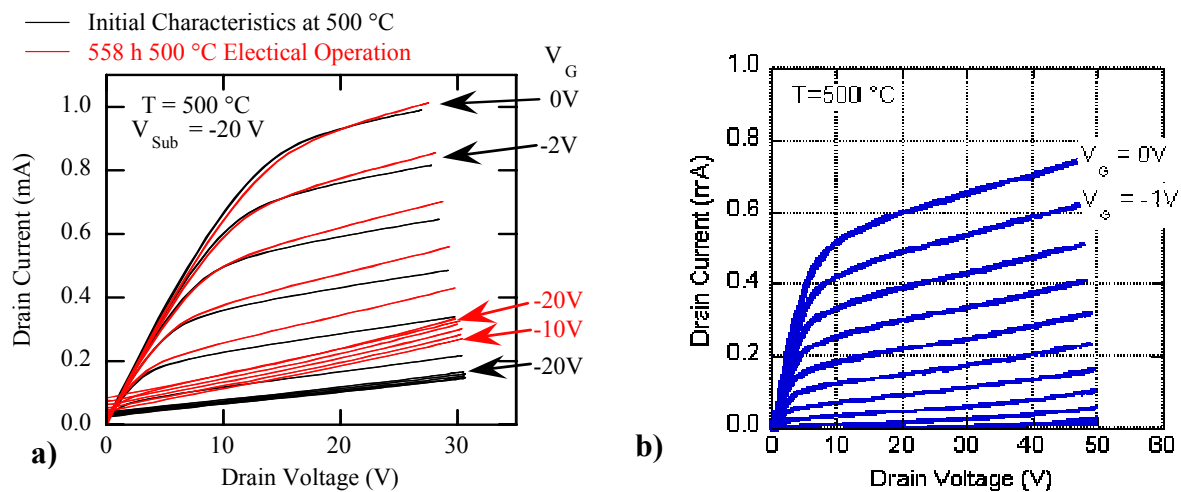


Figure 1. Drain current-voltage characteristics of two 6H-SiC transistors: a) Previous work of a device that electrically operated continuously for over 500 hours at 500 °C in oxidizing air ambient with minimal device degradation [10]. The device does not turn off completely and the initial (black) and final (red) I-V curves differ. b) Recent results of testing a device fabricated with improved processing techniques and exhibiting excellent behavior including low turn-off current. Significant improvement in device properties is demonstrated.

Using the Ti/TaSi<sub>2</sub>/Pt high temperature n-type ohmic contact discussed above, a high temperature n-channel 6H-SiC metal semiconductor field effect transistor (MESFET) demonstrated previously unattained 500°C transistor electronic durability. The MESFET operated continuously for over 2400 hours at 500°C [9]. Unfortunately, the MESFETs from this wafer all suffered from incomplete turn-off of channel current and the gradually increasing leakage of the metal-semiconductor gate-to-channel diode with 500°C operating time, and eventually resulted in failure of the device. For the first 500 hours, the device underwent less than 10% change in operational transistor parameters. Figure 1a compares the operating characteristics before (black) and after (red) 558 hours of continuous electrical operation at

500 °C of this MESFET [10]. The dominant degradation mechanism of this MESFET was due to annealing of the metal-semiconductor gate interface. The inability of the transistor to turn-off completely including the slope in the Figure 1a drain I-V characteristics was caused by a simple fabrication error [10].

By implementing a relatively minor process change, the durability-limiting metal-semiconductor gate failure has recently been eliminated. The details of the fabrication and results of long-term testing of these devices will be detailed elsewhere (11). These devices use nearly the same ohmic contact, dielectric passivation, epilayers, and packaging technology demonstrated to be capable of prolonged 500°C operation. However, as shown in Figure 1b, the JFET devices exhibit excellent I-V characteristics at 500°C, including low turn-off current and the absence of “looping” IV hysteresis. In other words, these results suggest operation of JFET devices with acceptable device functionality as one might see in Si devices, but at 500°C.

This capability is, to our knowledge, a world-first at this temperature and enables a range of new device possibilities. For example, simple JFET integrated circuits have also been implemented on the same wafer and tested on a probing station at 500°C. A NAND and NOR gate was fabricated and demonstrated on a probe station with good response characteristics. These building blocks are among the basics of circuit operation. In principle, this capability can enable Apollo era electronic processing capability, but at temperatures of 500°C. Further testing is underway to determine the durability of these devices in a packaged system.

### **Sensor Technology Development: SiC-Based Gas Sensors**

The semiconductor properties of SiC combined with its inherent durability, inertness, and piezoelectric properties allow for its use as a sensor material as well as an electronic material. A range of sensors are presently being developed from SiC including pressure sensors, accelerometers, and flow sensors (6,12-14). Due to the use of SiC as a starting material, each sensor has a range of inherent advantages as well as technical development challenges. This section describes the development of SiC-based gas sensors and is meant to show an example of the state-of-the-art in the field while illustrating some of the technical issues involved in development of SiC sensors operable at high temperature and/or harsh environments.

Silicon carbide based gas sensors have the ability to meet the needs of a range of aerospace applications. Two example applications include emission monitoring in high temperature ambients, and leak detection in lower temperatures ambients but with the sensor operating at higher temperatures. For emissions monitoring, the detection of the chemical signature of the emissions of a propulsion system may indicate the state of the combustion process and thus, the efficiency and health of the system. Ideally, an array of microfabricated sensors measuring the emissions stream at the exit of the propulsion system could provide information on the propulsion system state and would be a dramatic step towards realizing the goal of monitoring/control of emissions produced by a propulsion system. Such a gas sensor array would, in effect, be a high temperature electronic nose. The development of such a High Temperature Electronic Nose has begun using high temperature gas sensors, and SiC gas sensor operation in the emission exhaust environments has been demonstrated (15,16).

SiC-based gas sensors also have application in less extreme ambient environments, but with the sensors still operating at higher temperature. One area of development is an integrated smart leak detection system for propulsion systems. The objective is to produce a microsensor array, which includes hydrogen ( $H_2$ ), oxygen ( $O_2$ ), hydrocarbons, and potentially hydrazine (16-18). A range of potential launch vehicle fuels (hydrogen, hydrocarbons, or hydrazine) and oxygen can be measured simultaneously to determine explosive conditions. The array is being incorporated with signal conditioning electronics, power, data storage, and telemetry with the surface area comparable to a postage stamp for a stand-alone system. The concept is to place these self-contained near postage-stamp sized sensors where needed in a “Lick and Stick” implementation mode. A prototype model of the “Lick and Stick” sensor system has been fabricated and SiC-based detection of jet fuel and oxygen has been demonstrated (18).

These applications require sensitive gas detection. Due to the nature of the detection mechanism, Schottky diodes can have a strong response to low concentration of gases, i.e., an exponential change in the forward current and a quadratic change in the capacitance in response to changes in the gas environment while the diode is under fixed bias (19-20). The emphasis in the NASA GRC SiC gas sensor program is to develop, largely due to its high sensitivity, the Schottky diode gas sensing structure. However, reliable operation of this structure, especially when the sensor is operated at high temperature, requires good control of the interface between the gas sensitive layers and the SiC semiconductor (21-24). There are two approaches being explored to better control the SiC Schottky diode interface for gas sensing applications.

The first approach is the use of a barrier layer between the metal and SiC. Without this barrier layer, reaction can occur between the gas sensitive metallic layer and the SiC. These reactions cause drift in the sensor response and degradation of the sensor. Materials such as chrome carbide or palladium oxide ( $PdO_x$ ) have been examined as potential barrier layers. These barrier layers have yielded sensors with high sensitivity and prolonged stability representing a marked improvement over a Pd/SiC Schottky diode sensor without a barrier layer (23-24). In contrast, the use of silicon dioxide or some surface treatments meant to inhibit surface reactions have, in fact, appeared to decrease the sensor sensitivity and/or stability (21-22).

The second approach is the use of atomically flat SiC to provide an improved SiC semiconductor surface for gas sensor element deposition. It is considered that this approach has perhaps the most potential to enhance SiC gas sensing overall. Commercially available SiC semiconductors have crystal defects and screw dislocations leaving the semiconductor surface rough and variable. The focus of the NASA GRC work is to provide atomically flat surfaces without defects for the fabrication of complete gas sensing structures. The first use of atomically flat SiC in sensing applications was discussed in reference (23). Figure 2a show an atomically flat (AF) and non-atomically flat (NAF) SiC Schottky diode gas sensor on the same chip while Figure 2b shows the results of side-by-side testing of the two samples. The samples were both exposed to 0.5%  $H_2$  in nitrogen and the gain (change in current/baseline current in air) was measured. At 200°C nearly the same response is measured from both sensors. The difference in response between these two sensors takes effect when the sensor is heated to 300°C and is easily evident in Figure 2b. The AF sensor gain increases dramatically compared to the NAF sensor and stabilizes near 325 hours into the testing or after nearly 200 hours at 300°C. The gain of the AF sensor is

near 7250 while that of the NAF sensor is near 50. Thus, the gain of the AF sensor response averages nearly 145 times greater than that of the NAF sensor. These preliminary results have suggested a strong advantage to the use of on-axis and atomically flat SiC over the standard materials on which SiC Schottky diode gas sensors are fabricated.

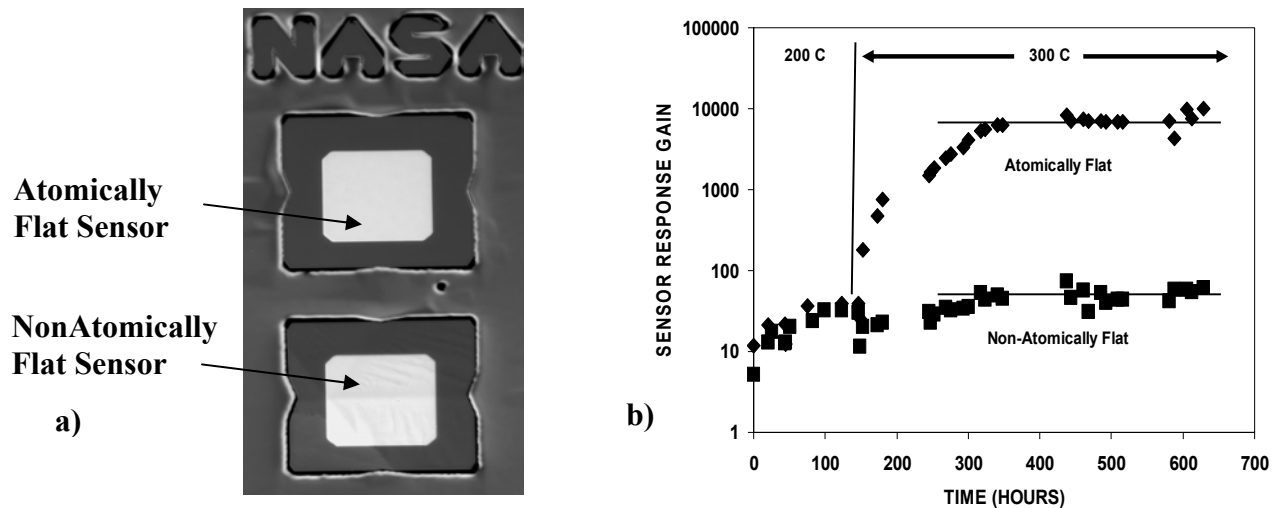


Figure 2. Demonstration of atomically flat SiC gas sensor responses from reference (23): a) Side by side sample of AF and NAF sensors. The bottom is the non-atomically flat sensor and the top is the atomically flat sensor. Surface differences between the two sensors are significant and include hillock morphology from a screw dislocation on the bottom mesa. b) Comparison of sensor gain to 0.5% hydrogen between Pt/SiC sensors deposited on atomically flat SiC (◆) and non-atomically flat SiC (■). The difference in response between the sensors at 300°C is easily observed.

Recent work has involved moving from the basic atomically flat mesa structure holding only a sensor, as shown in Figure 2a, towards an atomically flat structure that includes the components necessary for an operational gas sensor. Such a structure would not only include the gas sensitive Schottky diode, but also a temperature detector and heater to control the sensor's temperature in variable thermal environments. The approach is to develop a process to fabricate a small, complete sensing structure with minimal thermal mass such as those formed in silicon structures (16). Such capabilities are necessary if the full potential of atomically flat SiC gas sensors is to be achieved in compact microsystems.

Atomically flat or step-free surfaces were produced on commercially purchased on-axis 4H-SiC wafers in the following general manner [24-26]. First, dry reactive ion etching (RIE) was used to form 30  $\mu\text{m}$  deep trenches into the wafer surface to form an array of isolated growth mesas. Epitaxial growth is then used to grow all initial surface steps out to the edge of the mesa leaving behind a mesa with a topmost surface that is step-free. Only mesas that are not threaded by screw dislocations can be rendered step-free (i.e. atomically flat). Step-free mesas subjected to further growth will laterally evolve webbed cantilevered regions that extend out beyond the sidewalls at the top of the original mesa [25]. The resulting sensor structure shown in Figure 3a resides on top of an atomically flat SiC "tabletop" that

was mostly formed from lateral extension of SiC cantilevers grown from a much smaller pre-growth support mesa. A sensor pattern with a combined temperature detector/heater was deposited on the “tabletop” with dimensions near 0.6 x 0.3 mm and is shown in Figure 3a. A Pt/SiC Schottky diode is also shown in Figure 3a as the large contact pad in the center of the structure. A Pt resistor (with resistance  $\sim 50$  ohms) forms the temperature detector/heater composed of the thin line metal pattern adjacent to the Schottky diode. Experience in fabrication of silicon based gas sensor systems has been used in the design of this SiC device.

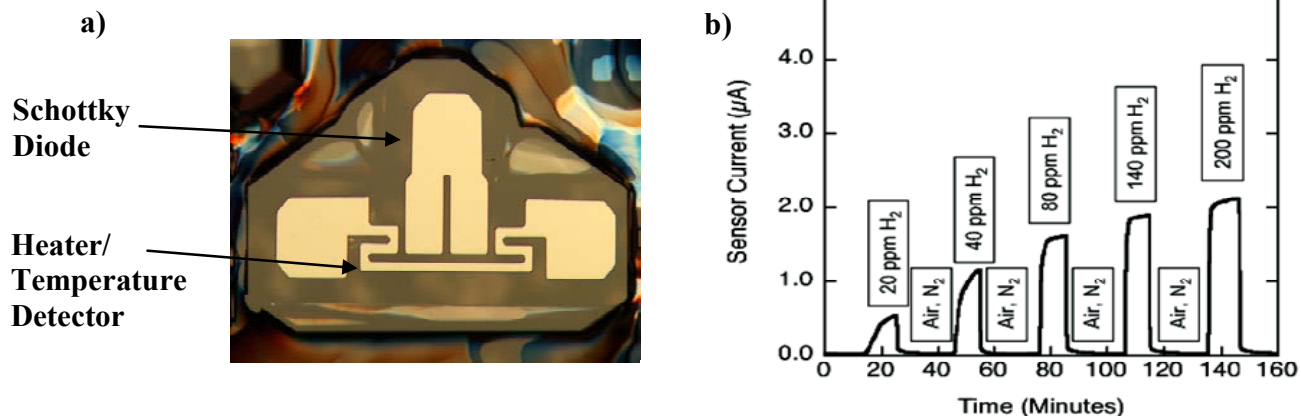


Figure 3. a) An atomically flat SiC mesa similar to the mesas shown in Figure 2, but now including both the Schottky diode gas sensor and a resistor for temperature control. b) Atomically flat SiC gas sensor response to hydrogen at a range of concentrations operated using its own heater at  $\sim 150^{\circ}\text{C}$ .

The results of preliminary testing of the sensor are shown in Figure 3b. The sensor is internally heated by the on-board heater/temperature detector to  $\sim 150^{\circ}\text{C}$ . The sensor is then exposed to increasing concentrations of 20 ppm to 200 ppm hydrogen in nitrogen. Sensitive detection of hydrogen is demonstrated throughout the concentration range. To our knowledge, this is the first demonstration of the operation of a complete atomically flat SiC Schottky diode gas sensor with integrated temperature control. Based on the results of this testing, modification of the atomically flat SiC sensor pattern will be performed. The long-term goal is to produce complete, operational SiC gas sensors including the device structures pioneered in commercially available SiC, e.g., Pd/PdO<sub>x</sub>/SiC, while retaining the sensing advantages of atomically flat SiC.

### Packaging of Harsh Environment Sensors and Electronics

The operation of electronics and sensors in harsh environments requires packaging technologies beyond those for conventional electronics and sensors. For *in situ* monitoring of aerospace engines, sensors and electronics must operate at temperatures of  $500^{\circ}\text{C}$  and above. Thus, the packaging materials and basic components, such as substrate, metallization material(s), electrical interconnections, and die-attach must be operable and reliable in high temperature, harsh environments. These harsh environments are far beyond those which commercially available packaging technologies can withstand; therefore, development of high temperature, harsh environment packaging technologies is necessary. Recently,

ceramic (aluminum nitride and aluminum oxide) substrates and gold (Au) thick-film metallization based chip-level electronic packages [27] and printed circuit boards have been designed and fabricated for testing high-temperature devices. The electrical interconnection system of this advanced packaging system, including the thick-film metallization and wirebonds, has been successfully tested at 500°C in an oxidizing environment for over 5000 hrs with DC electrical bias. Electrically conductive die-attach materials with low curing temperature are also being developed for packaging of SiC devices.

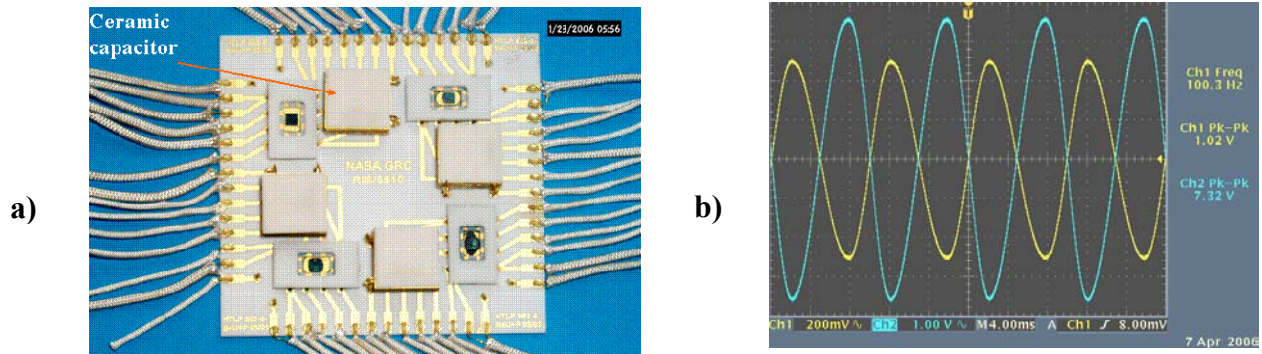


Figure 4. a) AC Amplifier Based on SiC MESFET and Ceramic Packaging (tested at 500°C for over 1100 hours). b) Waveform of input and output signals of amplifier circuit at 500°C and 100 Hz

The state of the art in application of this packaging technology is the successful demonstration of a 500°C low frequency AC voltage amplifier based on SiC devices and aluminum oxide substrate based packaging system [28]. Four testing units were integrated on an aluminum oxide ( $\text{Al}_2\text{O}_3$ ) printed circuit board (PCB). The amplifier circuit was composed of a SiC MESFET, two SiC on-chip resistors, and an aluminum oxide (96% $\text{Al}_2\text{O}_3$ ) chip-level package (Figure 4a). The amplifier was thermally soaked in a benchtop oven, and continuously tested with electrical bias. The high temperature amplifier demonstrated a voltage gain of 15 at room temperature, and a gain of 7 at 100Hz at 500°C, and was stable during approximately 688 hours of heat soak testing (Figure 4b) (28). The circuit began to degrade at that time due to the durability of the MESFET used, but the packaged circuit continued operation for over 1100 hours without degradation/failure of packaging system. The demonstration of durable and stable operation of a functional 500°C amplifier with packaging is a further step towards useful 500°C extreme environment electronics. The introduction of the improved JFET technology discussed in Figure 1 into packaging schemes such as those in Figure 4 is expected to have significant potential for enabling a range of high temperature circuits.

### Summary and Future Plans

Sensors and electronics for use in a range of aerospace applications and in Venus missions need to operate in harsh, high temperature environments. Three major technology areas were discussed. High temperature SiC electronics have been developed to the level that recently JFET, as well as NAND and NOR gates, have been demonstrated at 500°C. The basic material properties of SiC including crystal level material defects are being addressed with the formation of integrated SiC gas sensors fabricated using atomically flat SiC mesas. The ability to integrate multiple devices in a durable high temperature



packaging system was also demonstrated. Overall, significant progress has been made in maturing SiC based sensor and electronics technology up to 500°C. While more work needs to be done, the technologies shown are the core tools that will enable future development.

One technology area which would significantly change the use of sensor systems at 500°C is the development of high temperature wireless communication combined with integrated data processing i.e. a smart sensor. Wires can limit the reliability of a sensor system given that they are one of the major causes of sensor failure. They also add size, weight, and complexity to a system. Local data processing in hot environments can improve the accuracy of the sensor output and allow a sensor system to internally perform functions such as self-checks or hold calibration tables. While smart sensor technology is presently finding implementation in some lower temperature aerospace applications, smart sensors operating at high temperatures such as 500°C do not exist because the electronics and packaging to enable the high temperature “smart” system do not exist.

This paper has described what we understand to be the state-of-the-art in the basic technologies of electronics and packaging to enable high temperature smart sensor systems. Combined with other technologies, such as passive devices (e.g. resistors and capacitors) and power scavenging, a longer-term goal is the development of a sensor system composed of sensors, signal conditioning, power, and wireless communication. In effect, this stand-alone smart sensor system would be a high temperature version of the “Lick and Stick” technology discussed earlier. While system integration would be a challenge that would need to be addressed for harsh environments, such a “High Temperature Lick and Stick” system would allow sensors to be placed where they are needed without the complication of wiring associated with communication or power. Such a “High Temperature Lick and Stick” system would fundamentally change how sensors are implemented in high temperature applications. Further development towards that goal is on-going based on the types of technologies discussed in this paper.

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