

# HIGH TEMPERATURE ELECTRONICS, COMMUNICATIONS, AND SUPPORTING TECHNOLOGIES FOR VENUS MISSIONS

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## ABSTRACT

NASA Glenn Research Center is presently leading the development of electronics and sensors capable of prolonged stable operation in harsh 500°C environments. These technologies are being developed for engine environments but also have Venus planetary exploration applications. This paper discusses these high temperature electronic and sensor technologies as well as their relevance to Venus missions. A specific application describing a Venus instrument, a Venus Integrated Weather Sensor (VIWS) System, is described.

## 1. INTRODUCTION

NASA Glenn Research Center (GRC) is presently leading the development of electronics and sensors capable of prolonged stable operation in harsh 500°C environments. These technologies are being developed for engine environments but also have Venus planetary exploration applications. 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 duration (on the order of hours) of data collection and return. The ability of a spacecraft (including its electronics) to function and return useful data for far longer time periods (months) would undoubtedly greatly improve the scientific return gained from Venus surface missions.

For example, the recent emergence of wide bandgap semiconductors, including silicon carbide (SiC), diamond, and gallium nitride (GaN), has enabled short-term electrical device demonstrations at temperatures from 500°C to 650°C [1]. Until recently however, these wide bandgap devices have demonstrated only a few minutes to a few hours of durability when electronically operated at these high temperatures. In order to support the needs of long-duration Venus surface operations, wide bandgap electronics technology must first demonstrate that it

can achieve stable, long-term operation under electrical bias at 450°C temperature without significant changes in electrical operating parameters.

NASA GRC is a world-leader in harsh environment electronics and sensor technology [2] and is uniquely positioned to contribute to future Venus electronics systems. NASA GRC has developed SiC-based transistor technology (including packaging) that has demonstrated continuous electrical operation at 500°C for over 2000 hours [2,3]. No other reported semiconductor transistor has demonstrated such continuous prolonged electrical operation in an ambient comparable to or exceeding Venus atmospheric temperature. In contrast to other proposed high temperature electronics approaches (such as miniature vacuum tubes), the NASA GRC SiC transistor technology is inherently compatible with integrated circuit manufacturing techniques, so that increasingly complex electronics could be implemented on a single SiC chip.

Development of high temperature wireless communication based on SiC electronics has also been on-going at NASA GRC. This work has concentrated on the SiC electronic devices as well as the passive components such as resistors and capacitors needed to enable a high temperature wireless system.

This paper discusses the development of SiC based electronics and wireless communications technology and its possible application in Venus missions. This electronics development includes the supporting technologies such as device contacts and packaging. Further, characterization of Venus surface conditions also requires durable lightweight sensor technology which can operate in harsh environments. A brief overview of relevant sensor technologies and their compatibility with SiC based electronics will be given. It is concluded that the base technologies being developed for engine applications can have a significant effect on possible Venus missions.

## 2. HIGH TEMPERATURE ELECTRONICS AND COMMUNICATIONS

The ability to process, amplify, and even wirelessly transmit signals directly from the point of harsh-environment sensing would have clear benefits in a variety of aer propulsion systems. 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, such as cooling, at or near very hot combustion chambers and exhaust gas streams. While conventional 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].

Silicon carbide (SiC) presently appears to be the strongest candidate semiconductor for implementing 400-600 °C integrated electronics, as competing high temperature electronics technologies are either physically incapable of functioning at these high temperatures (silicon and silicon-on-insulator), or are significantly less-developed (GaN, diamond, etc.). 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 semiconductor discrete devices and integrated circuits. SiC devices such as pn junction diodes, Junction Field Effect Transistors (JFETs), and Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) have previously demonstrated reasonable electrical functionality at high temperatures for relatively short time periods [4,5]. However, for such electronics to be useful in engine applications, much longer lifetimes at 400 to 600 °C must be realized. Acceptable levels of durability and reliability must be attained before high temperature electronics will qualify for beneficial insertion into a broad variety of systems. Therefore, more than any other metric such as transistor power, gain, or frequency, NASA GRC's SiC electronics technology development is focused on realizing increasingly prolonged 400-600°C electronic operation.

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 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.

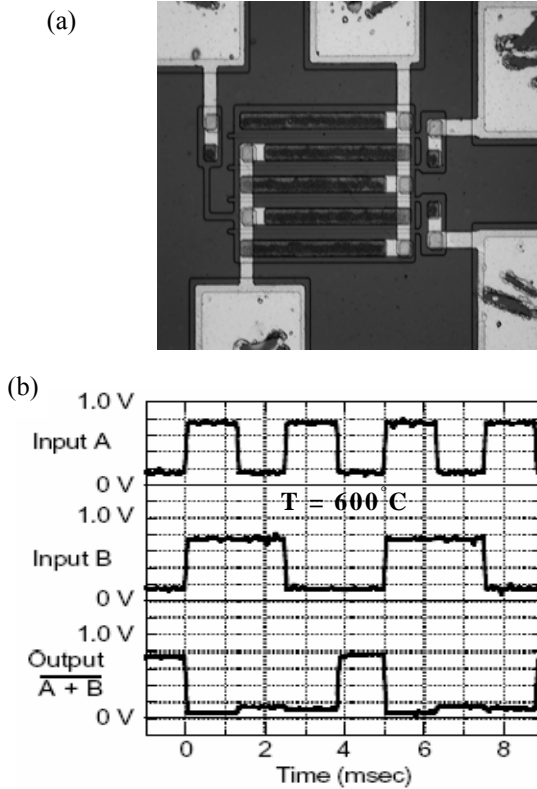


Fig. 1. (a) Optical micrograph and (b) 600 °C functional electrical testing waveforms of 6H-SiC JFET-based NOR logic gate. Supply voltages used for electrical testing were  $V_{DD} = 3.5$  V,  $V_{SS} = 0$  V, and  $V_{substrate} = -1.8$  V [6].

An example of the maturity level of SiC JFET technology over seven years ago was the demonstration of 600°C digital logic using SiC JFETs (Fig. 1) [6]. A resistive load Direct-Coupled FET Logic (DCFL) approach was adopted to demonstrate simple 600°C digital logic using SiC JFETs. A mesa-etched epitaxial gate JFET design was chosen over that of a planar ion-implanted structure, largely to alleviate the challenging process of sufficiently activating high-dose p<sup>+</sup> ion implants in SiC. The two-level interconnect approach used oxidation-resistant 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 (i.e. low technology readiness level) 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 [7]. 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 (which by itself is quite a difficult challenge given large temperature extremes). It also simplifies the design of SiC-based electronic sensing elements desired to monitor high temperature processes, such as pressure sensors and gas sensors described elsewhere in this paper.

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. Fig. 2a shows a scanning electron micrograph of the device, whose fabrication and characterization are described in much greater detail elsewhere [3]. Fig. 2b compares the operating characteristics before (black) and after (gray) 558 hours of continuous electrical operation at 500°C. For the first 500 hours, the device underwent less than 10% change in operational transistor parameters. 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 Fig. 2 drain I-V characteristics) was caused by a simple fabrication error [3]. By implementing a relatively minor process change, the degrading metal-semiconductor gate can be replaced with a pn junction gate, thereby forming a more durable junction field effect transistor.

Such JFETs are presently being fabricated at NASA GRC. Aside from the gate-related degradation, all other aspects of the MESFET demonstrated excellent harsh-environment stability while operating for over 2000 hours under prolonged electrical bias at 500°C. The prolonged high temperature electrical testing of the MESFET was enabled by packaging technology discussed elsewhere in this article, as probe-station testing over long time periods at 500°C is largely impractical.

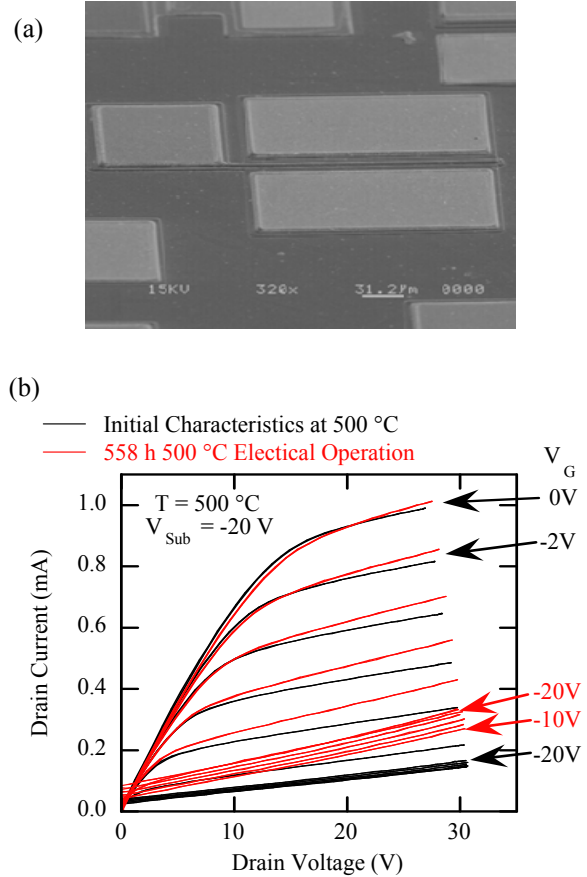


Fig. 2. (a) Scanning electron micrograph and (b) drain current-voltage characteristics of a 6H-SiC transistor that electrically operated continuously for over 500 hours at 500 °C in oxidizing air ambient with minimal device degradation [3]. The initial (black) and final (gray) I-V curves differ slightly due to degradation of the metal semiconductor gate contact, a mechanism which can be eliminated by implementing a pn junction gate transistor process (see text).

Integrated circuits require interconnects to carry electrical signals between the various transistors on the semiconductor chip. However, long-term electrical operation of dielectrics with microscopically patterned metal traces in an oxidizing 400-600°C environment has not (to the best of our knowledge) previously been demonstrated. Therefore, NASA GRC is also pursuing fundamental materials and processing development of this critical building block needed to implement extreme temperature integrated circuit electronics.

Recently, a high temperature, low frequency common-source voltage amplifier based on a SiC MESFET, SiC resistors, and high temperature ceramic packaging was successfully demonstrated at 500°C [8]. Both voltage

gain and frequency response were reasonably stable during the entire testing period of 1100 hours at 500°C.

Work has also been on-going to integrate SiC electronics with high temperature passive devices to produce a high temperature wireless communications system. The passive devices include capacitors and resistors able to work at high temperatures and frequencies. The objective is to eliminate wires associated with high temperature sensors which add weight to a vehicle and can be a cause of sensor unreliability.

A high-temperature measurement system capable of performing on-wafer microwave testing of semiconductor devices has been developed [9]. This high temperature probe station can characterize active and passive devices and circuits at temperatures ranging from room temperature to above 500°C. The heating system is comprised of a ceramic heater mounted on an insulating block of NASA shuttle tile material. The temperature is adjusted by a simple graphical computer interface and is automatically controlled. The system is used with a Hewlett-Packard 8510C Network Analyzer to measure scattering parameters over a frequency range of 1 to 50 GHz. The microwave probes, cables, and inspection microscope are all shielded to protect them from heat damage. The high temperature probe station has been successfully used to characterize gold transmission lines on silicon carbide at temperatures up to 540°C.

Passive devices for communication purposes which have been formed include thin film nickel chromium (NiCr) resistors, metal-insulator-metal (MIM) capacitors, and spiral inductors fabricated on a high purity semi-insulating 4H-SiC substrate [10]. The devices have been experimentally characterized through 50 GHz at temperatures up to 500°C. The NiCr resistors are stable to within 10% to 300°C while the capacitors have a value stable within 10% through 500°C. Inductors are expected to be fully stable through 500°C with a redesign of the associated air bridges.

A critical component of a wireless sensor system is the local oscillator that generates the RF signal, which will be modulated by the sensor and data will be transmitted to cooler environments. Integration of passive components with a commercially available SiC MESFET was performed to demonstrate the ability to design the circuit, the operability of the passive components, and the integration of the components with a SiC device [6,11]. The temperature characteristics of the Cree 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 designed to operate at 1 GHz instead, which operated at 500 MHz due to drift in the transistor capacitance with temperature. However, this circuit did operate at 475° C with an output frequency of 453 MHz [6] into a non-50 Ω load. A second circuit, a Clapp Oscillator that has less dependence on the transistor capacitance, was designed and is shown in Fig. 3. Testing showed that it operates at 1 GHz into a 50-Ω load over the temperature range of 30 to 200° C. with an output power of 21.8 dBm at 1 GHz and 200°C. The frequency variation over the temperature range is less than 0.5%. The efficiency at 200°C is 15%. Modeling predicted that the circuit should have operated through 300° C, but increased loss in the passive devices limited the operation.

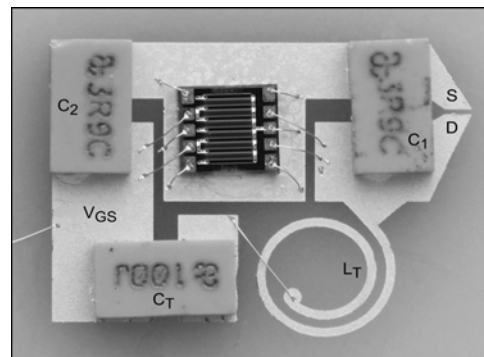


Fig. 3. Photograph of oscillator comprised of SiC MESFET, ceramic chip capacitors, a spiral inductor, and gold wire bond interconnects.

This oscillator was a proof-of-concept device to show the viability of the design approach. It also showed that greater gain is required from the transistors if they are to operate at 1 GHz and temperatures above 300° C. Moreover, it is noted that the transistor characteristics 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 that 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 performance [12].

As noted, work is on-going at NASA GRC to advance the state-of-the-art of the SiC devices, and work is planned to improve the passive devices. Overall, the ability for high temperature wireless communication to operate up to Venus temperatures is envisioned within

the next 5 years at the present rate of development (and sooner if concentrated effort is applied to the problem). Communication at lower temperatures, e.g., below 250°C, is envisioned to be achievable in a shorter time frame using techniques such as silicon on insulator or SiGe.

A parallel approach to using a SiC MESFET is to use atomically flat SiC as a substrate for growing gallium nitride (GaN) and then using GaN on SiC for communication purposes. This approach allows use of the favorable properties of GaN, provided durable high temperature operation can be obtained with this material. Recent data has shown a significant decrease in defects of GaN on SiC by using atomically flat SiC with a world-record 100 fold defect reduction [13].

### 3. PACKAGING OF HARSH ENVIRONMENT SENSORS AND ELECTRONICS

The operation of electronics and sensors in propulsion 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°C and above. Thus, the packaging materials and basic components, such as substrate, metallization material(s), electrical interconnections (such as wire-bonds), and die-attach must be operable and reliable in high temperature (500°C) and chemically reactive (especially oxidizing and reducing) environments. These packaging components may also experience high dynamic pressure and high acceleration, depending on the application. These harsh operation environments are far beyond those which commercially available packaging technologies can withstand; therefore, development of high temperature, harsh environment packaging technologies is necessary to implement high temperature sensors and microelectronics in aeronautic and space propulsion systems as well as Venus missions.

Ceramic substrates and precious metal thick-film metallizations have been proposed for packaging of harsh environment electronics and sensors, based on their excellent stability at high temperatures and in chemically reactive environments [14,15]. As a packaging substrate material, aluminum oxide has acceptable variation of dielectric constant and dielectric loss in the temperature range from 25 to 500°C for a wide frequency range. Aluminum nitride was proposed to package high temperature SiC MEMS and power devices because it possesses a low thermal expansion coefficient [16] and high thermal conductivity.

Recently, ceramic (aluminum nitride and aluminum oxide) substrates and gold (Au) thick-film metallization based chip-level electronic packages (Fig. 4a) [2,17] and printed circuit boards (Fig. 4b) 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 hours with DC electrical bias. Electrically conductive die-attach materials with low curing temperature are being developed for packaging of SiC devices.

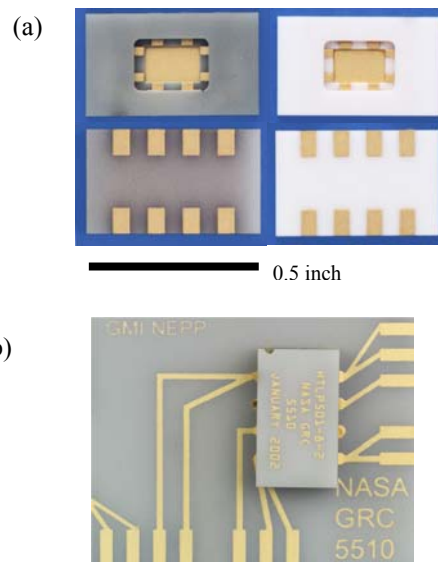


Fig. 4. (a) AlN (left) and Al<sub>2</sub>O<sub>3</sub> (right) high temperature chip-level packages. (b) AlN PCB designed for AlN packages.

An 96% aluminum oxide based packaging material system was successfully used to facilitate the test, previously described above, of an in-house-fabricated SiC MESFET under electrical bias in a 500°C air ambient for more than 2000 hrs [2,3]. Fig. 2b shows the transistor current-voltage characteristics at the start of the test and after 558 hours of continuous electrical operation in air at 500°C. The packaging components continued to successfully operate without observable electrical degradation for the full duration of the 500°C test that exceeded 2000 hours in duration. Further, the demonstration of a functional 500°C amplifier, discussed above, highlights the most recent progress in printed circuit board level packaging and passive devices for 500°C [8] and is a significant step towards 500°C and Venus relevant applications. The board packaging is shown in Figure 5.

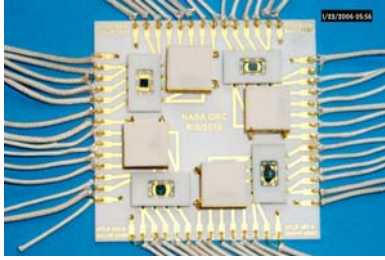


Fig. 5. The test assembly of 500°C amplifiers based on SiC MESFETs and aluminum oxide packaging system. The test assembly includes four amplifier circuits.

#### 4. SENSOR TECHNOLOGY DEVELOPMENT

A range of sensor developments applicable to Venus missions is in progress at NASA GRC. The sensor development includes pressure sensors, thin film sensors, and chemical sensors. Each of these sensor types will be described briefly in the subsections that follow. A more detailed description is found in a separate paper presented at this conference [18].

##### 4.1 High Temperature SiC Pressure Sensors

Conventional pressure sensors are temperature limited while SiC-based pressure sensors have a much wider temperature range and have the added benefit that high temperature SiC electronics can be integrated with the sensor. Progress has been made in both SiC pressure sensor micromachining and packaging [19]. The resulting sensors have demonstrated the capability to withstand high temperatures with improved reliability and operation up to 600°C [20]. These temperature ranges are more than adequate for Venus applications. Furthermore, the high temperature operation (600°C) of a SiC pressure sensor and anemometer has been previously demonstrated as separate discrete sensing devices. Ongoing research effort is geared towards integrating three functionalities by the utilization of advanced SiC MEMS Microsystems technology: a pressure sensor, an anemometer, and a fully passivated resistance temperature differential sensor [21].

##### 4.2 Thin Film Physical Sensors

NASA GRC has an in-house effort to develop thin film sensors for surface measurement in propulsion system research. The sensors include those for strain, temperature, heat flux, and surface flow which will enable critical vehicle health monitoring of future space and air vehicles [22,23]. One area of development is a patented thin film multifunctional sensor which integrates into one "smart" sensor the designs of individual gauges that

measure strain magnitudes and direction, heat flux, surface temperature, and flow speed and direction [24,25]. Various prototypes of the gauge have been bench tested on alumina substrates [25]. Future testing will include measuring all of the parameters simultaneously on a component to be tested in an engine environment. Thus, in one sensor system, a range of physical parameters regarding the immediate environment can be measured in Venus relevant environments.

#### 4.3 Chemical Sensor Technology

The development of MEMS-based chemical microsensors to measure emissions in high temperature, harsh environments has been on-going for a considerable time for emission monitoring applications [26]. A first generation chemical microsensor array (High Temperature Electronic Nose) has been demonstrated on a modified automotive propulsion system. The High Temperature Nose showed the ability to detect nitrogen oxides ( $\text{NO}_x$ ), oxygen ( $\text{O}_2$ ), and hydrocarbons ( $\text{C}_x\text{H}_y$ ). These results are qualitatively consistent with what would be expected for this type of engine. They also show the value of using sensors with very different response mechanisms in an electronic nose array: the information provided by each sensor was unique and monitored a different aspect of the engine's chemical behavior. These sensors have direct application in detecting multiple chemical species in Venus relevant environments. Overall, a potential chemical sensor array can be tailored for mission needs.

#### 5. POSSIBLE VENUS APPLICATIONS

The preceding pages discuss a range of NASA GRC high temperature electronics and sensor technologies. While these electronics and sensors were intended for aeronautics applications, these devices and supporting technologies have significant application in Venus missions. One illustrative example of the use of the high temperature electronics and sensors is to enable a Venus Integrated Weather Sensor (VIWS) System. The purpose of this instrument would be to provide the base technology to characterize the surface of Venus *in situ* by simultaneously measuring pressure, temperature, wind velocity, seismic activities, and chemical species as well as local temperature and heat flux on the surface and above the surface of Venus. Thus, this instrument provides weather and surface climate information from a sensor system directly exposed to the environment and able to operate for extended durations. This instrument might include the following technologies:

**Atmospheric Physical Sensors:** The use of silicon carbide (SiC) to sense pressure changes (absolute pressure

sensor), wind velocity (cantilever based anemometer), and resistance temperature differential. These three functionalities are integrated on a single weather sensor chip to characterize atmospheric conditions.

**Atmospheric Chemical Sensors:** An extension of a MEMS High Temperature Electronic Nose to measure species including carbon monoxide, sulfur dioxide, hydrocarbons, nitrogen oxides, and oxygen. The approach is to use platform technology tailored to measure chemical gas species as required to characterize atmospheric constituents.

**Surface Condition Physical Sensors:** Multifunctional thin film sensors to measure surface temperature, strain, and heat flux in a single MEMS based sensor. This would enable monitoring of local thermal conditions embedded on a surface both to understand the surface conditions and also to provide information on vehicle conditions.

Therefore, this technology can very feasibly be incorporated into small and lightweight functional modules (without need for a cooling system), in order to help maximize scientific return while minimizing exploration vehicle size and weight. These multiple component technologies will be modularized onto a single platform. Thus, in a single sensing system, pressure, wind velocity, temperature, chemical species, as well as strain and heat flux can be measured. The approach would focus on integrating even more reliable and complex high temperature electronics and sensors into a small functional module to collect and transmit sensor data from the Venus surface for prolonged (as long as power can be supplied) durations.

The overall advantage of this approach is that using harsh environment electronics and sensors provides a multi-parameter weather and environment monitoring system which is able to operate *in situ* in Venus environments. The range of physical and chemical information available is broad and can significantly contribute to understanding the Venus environment. These ceramic MEMS sensing units and wide bandgap semiconductor electronics are operable in Venus environments without the need for a cooling system, and thus are small and lower in power consumption relative to conventional weather instruments. Other advantages include the fact that these systems are meant for engine operation and so the near chemical inertness of the starting materials, esp. SiC, makes them highly resistant to chemical attack. Being small and lightweight allows high resolution, broad terrain coverage, or distribution using Venus wind as a dispersal agent.

## 6. SUMMARY

NASA Glenn Research Center (GRC) is presently leading the development of electronics and sensors capable of prolonged stable operation in harsh 500°C environments. These technologies have the capability to enable new Venus missions without cooling of electronics and sensors while greatly improving the scientific return gained from Venus surface missions. One example of such improved capabilities is a possible Venus Integrated Weather Sensor (VIWS) System which can measure *in situ* a range of Venus atmospheric conditions as well as vehicle parameters in a miniature system. Further, with the inclusion of high temperature electronics and wireless communications, the data can be processed and wirelessly communicated enabling new Venus missions.

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