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. This includes basic transistor, NAND gate, NOR gate, voltage amplifier, and RF circuit demonstrated at 500°C. 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 operate 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 operating at these high temperatures. In order to support the needs of long-duration Venus surface operations, wide bandgap electronics technology must first achieve stable, long-term operation under electrical bias at 450°C temperature without significant drift 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 solid state transistor technology is inherently compatible with integrated circuit manufacturing techniques, so that increasingly complex integrated electronics could be implemented on a single SiC chip. This paper reports on further advances in this technology and reports significant and new capabilities of relevance to Venus missions.

Development of high temperature wireless radio frequency (RF) 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 technology. Further, characterization of Venus surface conditions also requires durable lightweight sensor technology that can operate in harsh environments. A brief overview of relevant sensor technologies and their compatibility with SiC based electronics is given. It is concluded that the technologies being developed for engine applications can also provide a base technology to significantly enhance 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 clearly benefit a variety of aeropropulsion 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 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 are accepted and 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.

Metal-semiconductor contacts were one of the primary factors limiting high temperature device operational lifetime. Focused fundamental research to develop more durable SiC high-temperature ohmic contacts was undertaken to address the problem. These efforts produced a remarkably durable Ti/$TaSi_2$/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 [6]. Using Ti/$TaSi_2$/Pt high temperature n-type ohmic contacts, 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 [7]. 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. 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 was caused by a simple fabrication error [8].

By implementing a relatively minor process change, the durability-limiting metal-semiconductor gate failure has recently been eliminated. Figure 1 shows a cross-sectional schematic of the JFETs with the successfully implemented pn junction gate. A number of steps are involved in fabricating this device and are presently predominately performed in the NASA GRC Microsystems Fabrication Facility. The details of the fabrication and results of long-term testing of these devices will be detailed elsewhere [8]. These devices use the 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 2, the JFET devices exhibit excellent I-V characteristics at 500°C, including low turn-off current (with ION/IOFF ratio of around 50 at 50 V drain bias) and absence of "looping" IV hysteresis. In other words, these results suggest operation of 500°C JFET devices with acceptable device properties.

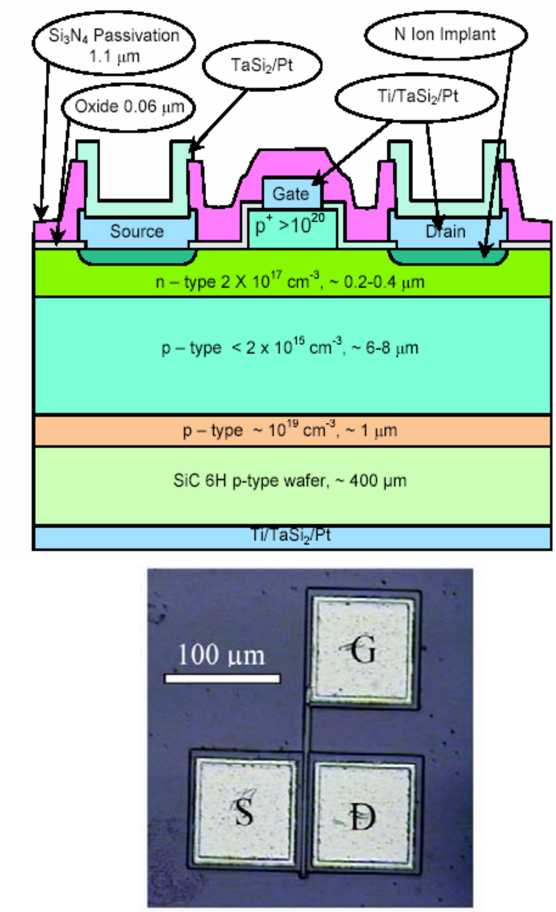

Fig. 1. Schematic cross-section and optical micrograph of 6H-SiC JFET.

Simple JFET integrated circuits have also been implemented on the same wafer and tested on a probing station at 500°C. A NAND gate with 10 V logic swing that was fabricated using top bondpad metallization residing on top of dielectric passivation for interconnect is shown in Figure 3. NOR gate operation was also demonstrated at 500°C with a similar high degree of functionality.

If proved durable at 500°C, this capability is a world-first to our knowledge that would enable a range of new device and mission possibilities. These building blocks are among the basics of circuit operation. In principle, this capability can enable Apollo era processing capability, but at temperatures of 500°C which are relevant for Venus missions. Further testing is underway to conclusively determine the 500°C long-term durability of these devices in a packaged system.

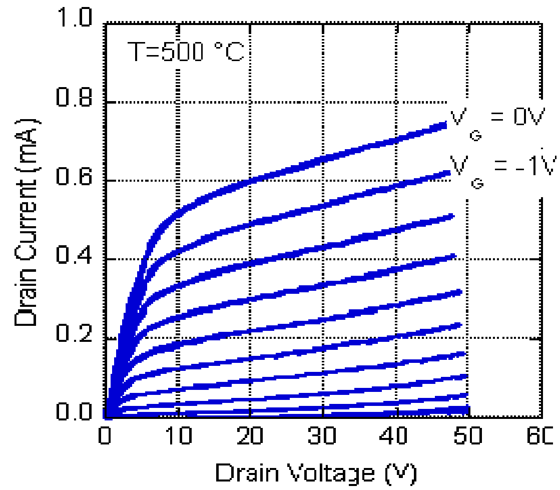

Fig. 2. Drain current-voltage characteristics of 6H-SiC JFET at T=500°C.

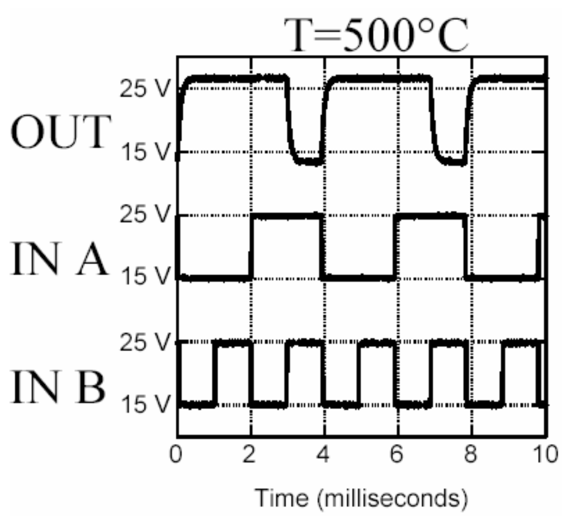

Fig. 3. 6H-SiC JFET-based NAND integrated circuit operational waveforms recorded during 500 °C probe test.

If these devices/circuits are operational for long duration at high temperatures, the technology described above could revolutionize harsh environment electronics operation and what could be conceived possible in Venus missions. The ability to produce long term reliable logic gates enables the production of complex logic structures such as flip-flops which then enable the formation of state machines. State machines enable the configuration of intelligent data transmission methods allowing for unambiguous demodulation of signals uniquely associated with each transmitter in a network. Further, state machines allow for the creation of control electronics for an "intelligent" fixed or mobile agent on Venus. Different sensed variables such as obstacles or temperature can be used to initiate state transitions allowing the agent to react appropriately.

Further, a high temperature, low frequency common-source voltage amplifier based on a SiC MESFET, SiC resistors, and high temperature ceramic packaging was recently successfully demonstrated at 500°C [9]. Both voltage gain and frequency response were reasonably stable during the entire testing period of 1100 hours at 500°C. This amplifier was based on the previous MESFET technology; it is expected that further advances are possible using the more recent JFET technology of Figure 2.

Other work continues to advance the state-of-the-art of SiC semiconductor technology. 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.

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 [10]. 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 [11]. 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 [6,12]. 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. 4. 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 [12].

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 commercial 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 overall device performance [13].

As noted, the work is on-going at NASA GRC to advance the state-of-the-art of the SiC devices, as well as to improve the passive devices. Overall, the ability for high temperature wireless communication to operate up to Venus temperatures is envisioned within the next 4 years at the present rate of development (and sooner if a more 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.

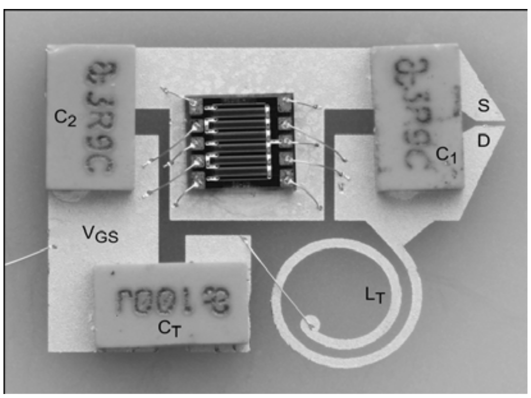

Fig. 4. Photograph of oscillator comprised of SiC MESFET, ceramic chip capacitors, a spiral inductor, and gold wire bond interconnects.

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 temperatre 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 [14].

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.

(a)

(b)

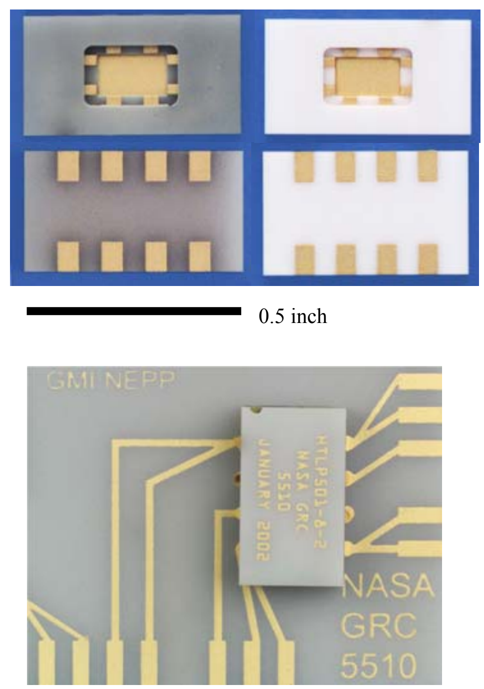

Fig. 5. (a) AlN (left) and Al_2O_3 (right) high temperature chip-level packages. (b) AlN PCB designed for AlN packages.

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 [15,16]. 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 [17] and high thermal conductivity.

Recently, ceramic (aluminum nitride and aluminum oxide) substrates and gold (Au) thick-film metallization based chip-level electronic packages (Fig. 5a) [2,18] and printed circuit boards (Fig. 5b) 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.

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]. 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 [9] and is a significant step towards 500°C and Venus relevant applications. The board packaging is shown in Figure 6.

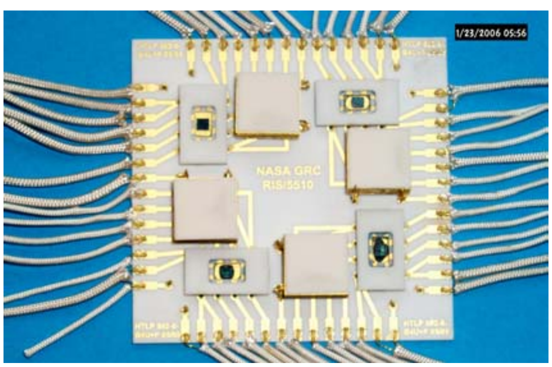

Fig. 6. The test assembly of 500°C amplifiers based on SiC MESFETs and aluminum oxide packaging system. The test assembly includes four test circuits.

Substrates and packaging material are also required for integrating various components of the RF wireless sensor. Characterization of RF transmission lines on Alumina (99.6 %) and sapphire as a function of temperature and frequency have been completed as well. It is found that on r-Sapphire, between 5 and 25 GHz, the attenuation increases nearly linearly at a rate of 0.0021 (dB/cm/°C). It is seen that the effective permittivity of the transmission line on r-Sapphire increases linearly with temperature with a slope of 0.0012 /°C. Results on Alumina are similar. While these results show that the effects of temperature must be accounted for in circuit design, the variations with temperature are not great enough to eliminate these substrates for use. For example, a narrow band antenna was fabricated and characterized as a function of temperature. It is found that the optimum radiating frequency determined by minimum return loss varied by 5%, but the radiation pattern does not change as a function of temperature.

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 [19].

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 [20]. The resulting sensors have demonstrated the capability to withstand high temperatures with improved reliability and operation up to 600°C [21]. 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 [22].

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 [23,24]. 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 [25,26]. Various prototypes of the gauge have been bench tested on alumina substrates [26]. 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 [27]. 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 (NO_x), oxygen (O_2), and hydrocarbons (C_xH_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. FUTURE 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 space 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 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 data presented in this paper demonstrates basic electronic processing capabilities at a functional level of Apollo era computing systems but operable at 500°C to enable Venus missions.

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. This includes the recent development of SiC J-FET technology which has the processing capability of Apollo era computing systems. While further development and demonstration is necessary, 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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8. REFERENCES

1. Neudeck P. G., Beheim G. M., and Salupo C. S., 600°C Logic Gates Using Silicon Carbide JFET's, *Government Microcircuit Applications Conference Technical Digest*, 421-424, Anahiem, CA, 2000.
2, Hunter G. W., Wrbanek J. D., Okojie R. S., Neudeck P. G., Fralick G. C., Chen L.Y., Xu J., and Beheim G. M., Development and Application of High Temperature Sensors and Electronics for Propulsion Applications, accepted for publication for the Proceedings of the SPIE Defense and Security Symposium, 2006 Sensors for Propulsion Measurement Applications Workshop, 2006.
3. Spry D., Neudeck P., Okojie R., Chen L. Y., Beheim G., Meredith R., Mueller W., and Ferrier T., Electrical Operation of 6H-SiC MESFET at 500°C for 500 Hours in Air Ambient, 2004 IMAPS International High Temperature Electronics Conference, Santa Fe, NM, May 18-20, 2004.
4. Neudeck P. G., SiC Technology, in *The VLSI Handbook, The Electrical Engineering Handbook Series*, W.-K. Chen, Ed., CRC Press and IEEE Press, Boca Raton, Florida, 2000.
5. Neudeck P. G., Okojie R. S. , and Chen L.-Y., High-Temperature Electronics- A Role for Wide Bandgap Semiconductors, *Proceedings of the IEEE*, Vol. 90, 1065-1076, 2002.
6. R. S. Okojie, D. Lukco, L.Y. Chen, and D. J. Spry, *Reliability assessment of Ti/TaSi2/Pt ohmic contacts on SiC after 1000 h at 600 °C*, Journal of Applied Physics, vol. 91, pp. 6553-6559, 2002.
7. P. G. Neudeck et al.: Materials Science Forum, 556-557, p. 831 (2007).
8. D. J. Spry, P. G. Neudeck, L.Y. Chen, G. M. Beheim, R. S. Okojie, C. W. Chang, R. D. Meredith, T. L. Ferrier, M. J. Krasowski, N. F. Prokop, *Fabrication and Testing of 6H-SiC JFETs for Prolonged 500°C Operation in Air Ambient,* International Conference on Silicon Carbide and Related Materials 2007, Nara, Japan, October 14-19, 2007.
9. Chen L.Y., Spry D., and Neudeck P. G., Demonstration of 500°C AC Amplifier Based on SiC MESFET and Ceramic Packaging, presented at the 2006 HITEC Conference, Santa FE, NM, May 2006.
10. Schwartz, Z. D., Downey, A. N., Alterovitz, S. A., and Ponchak, G. E., “High-temperature RF probe station for device characterization through 500 º C and 50 GHz,” *IEEE Trans. on Instrumentation*, Vol. 54, No. 1, pp. 369-376, Feb. 2005.
11. Schwartz Z. D., Ponchak G. E., Alterovitz S. A., Downey A. N., and Chevalier C. T., Measurement of Thin Film Integrated Passive Devices on SiC through 500°C, *Proceedings of the 34th European Microwave Conference*, Vol. 1, 313- 316, 2004.
12. Schwartz Z. D., Ponchak G. E., “1 GHz, 200 ºC, SiC MESFET Clapp Oscillator,” *IEEE Microwave and Wireless Component Lett.*, Vol. 15, No. 11, pp. 730-732, Nov. 2005.
13. Levinshtein M. E., Rumyantsev S. L., Shur M. S., Gaska R., and Khan M. A., “Low frequency and 1/f noise in wide-gap semiconductors: silicon carbide and

gallium nitride," *IEEE Proc.- Circuits Devices System.*, Vol. 149, No. 1, pp. 32-39, Feb. 2002.
14. Eddy Jr. C.R., Bassim N. D., Mastro M.A., Henry R. L., Twigg M.E., Holm R. T., Culbertson J.C., Neudeck P.G., Powell J.A., and Trunek A.J., Reduction of Defects in GaN Epitaxial Films Grown Heteroepitaxially on SiC, proceedings of the 2005 International Conference on Silicon Carbide and Related Materials, Pittburgh, PA , Sept. 18-23, 2005.
15. Salmon J. S., Johnson R. W., and Palmer M., "Thick Film Hybrid Packaging Techniques for 500°C Operation", Transactions of Fourth International High Temperature Electronics Conference (HiTEC), Albuquerque, New Mexico, June 15-19, 1998.
16. Chen L-Y., Okojie R. S., Neudeck P. G., and Hunter G., Material System for Packaging 500°C MicroSystems, MRS Proceedings, Symposium N: Microelectronic, Optoelectronic, and MEMS Packaging, San Francisco, CA, April 16-20, 2001.
17. Chen L-Y., Hunter G., and Neudeck P.G., Silicon Carbide Die Attach Scheme for 500°C Operation, MRS 2000 Spring Meeting Proceedings-Wide-Bandgap Electronic Devices (Symposium T), San Francisco, CA, April 10-14, 2000.
18. Chen L-Y. and Hunter G., Al2O3 and AlN Ceramic Chip-level Packages for 500°C Operation, 2005 International High Temperature Electronics Conference (HiTEN), Paris, France, September 6-8, 2005.
19. Hunter G. W., Okojie R. S., Oberle L., Krasowski M., Neudeck P. G., Beheim G. M., Fralick G., Wrbanek J., and Greenberg P., Microsystems, Instrument Electronics, And Mobile Sensor Platforms, Fourth Annual International Planetary Probe Workshop, Pasadena, CA, June 27-30, 2006.
20. Okojie R. S., Savrun E., Nguyen P., Nguyen V., Blaha C., Reliability Evaluation of Direct Chip Attached Silicon Carbide Pressure Transducers, 3rd IEEE International Conference on Sensors, Vienna, Austria, October 24-27, 2004.
21. Okojie R. S., Beheim G. M., Saad G. J., and Savrun E., Characteristics of Hermetic 6H-SiC Pressure Sensor at 600°C, AIAA Space 2001 Conference and Exposition, AIAA Paper No. 2001-4652, Albuquerque, NM, August 28-30, 2001.
22. Okojie R. S., Fralick G. C., Saad G. J., Blaha C. A., Adamczyk J. J., and Feiereisen J. M., A Single Crystal SiC Plug-and-Play High Temperature Drag Force Transducer", Digest of Technical Papers for Transducers '03, pp. 400-403, IEEE Catalog Number 03TH8664C, The 12th International Conference on Solid State Sensors, Actuators and Microsystems, Boston, MA June 8-12, 2003.
23. Lei J. F., Martin L. C., Will H. A., Advances in Thin Film Sensor Technologies for Engine Applications, NASA TM–107418, Turbo Expo '97, Orlando, FL, June 2-5, 1997.
24. Martin L. C., Wrbanek J. D., and Fralick G. C., Thin Film Sensors for Surface Measurements, NASA/TM—2001-211149, September 2001.
25. Lei J. F., Fralick G. C., and Krasowski M. J., Microfabricated Multifunction Strain-Temperature Gauge, US Patent 5,979,243, November 9, 1999.
26. Wrbanek J.D., Fralick G. C., Martin L. C., Blaha C.A., A Thin Film Multifunction Sensor for Harsh Environments, NASA TM-2001-211075, AIAA–2001–3315, July 2001.
27. Hunter G. W., Liu C. C., Makel D., *MEMS Handbook Second Edition, Design and Fabrication*, CRC Press LLC, ed. M. Gad-el-Hak, Boca Raton, Florida, Ch. 11, 2006.