

Body of Knowledge (BOK) of Applications of High Temperature Wireless Data Transmission Systems in Aerospace Engine Technology

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Liang-Yu Chen

Ohio Aerospace Institute/NASA Glenn Research Center

Abstract

1. Introduction

Forty years after Intel's Gordon Moore predicted that the number of transistors of advanced commercialized microchips could be doubled every two years (Moore's Law [Moore, 1965]), today's Intel Pentium 4 microprocessor contains 42,000,000 transistors and operates at frequencies between 1.3 and 3.8 GHz. The fabrication wafer size has reached 300 mm in diameter, and a single line width of lithograph technology has attained 193 nm. Intel Fellow and Director of Technology Strategy, Paolo Gargini, predicted on the opening day of the 2004 Semicom West Conference that the microelectronics industry can continue to maintain Moore's Law for at least another 15 to 20 years. "On a practical level, however, besides the emerging technology such as quantum, optical, plastic, MEMS, and Si CMOS with traditional CMOS, heterogeneous integration of alternative technology is the way of the future and packaging technologies will offer the best solution". His statement stressed the increasingly important role of packaging technology in the field of electronics for today as well as the future.

In addition to the rapid development of Si technology in respect of higher device densities (number of devices per unit wafer area) and larger wafer processes, semiconductor technology has also developed rapidly in respect of new semiconductor materials such as wide/narrow band-gap materials, organic and flexible electronic materials, and lastly nano-materials. Some of these new materials can be used to fabricate electronic devices that are operable in harsh environments (e.g., high temperature, extremely low temperature, and life *in vivo* environments). One example is the single crystalline silicon carbide (SiC) semiconductor. The band-gap between the conduction band and the valence band of single crystal SiC is between 2.3 and 3.2 eV depending on the crystal structure. This compares with ~ 1.1 eV for single crystal Si. The wide band-gap allows SiC electronic devices to operate in an environment with temperatures up to 600 °C [Neudeck, 2000]. The increased charge carrier mobility (more specifically, the increased saturation carrier speed and field of wide bandgap WBG materials such SiC and GaN) make these materials favorable for high frequency applications [Trew, 2002] as well. Besides these new developments regarding the materials, the improvements in fabrication processes and device structures have led to a new generation of microdevices and micro-electro-mechanical systems (MEMS), that have revolutionized both sensing and actuating. As an example, innovative SiC microsystems composed of SiC MEMS sensors and electronics are able to detect various physical and chemical signals [Hunter, 2004 and Okojie 2004] in very high temperature environments such as compressor and exhaust sections of aerospace engines.

In recent decades, microelectronics technology has significantly influenced our lifestyles. Microcircuits are in use everywhere in our daily lives, from kids toys to supercomputers. Microelectronic devices have greatly improved the way that information is obtained, transmitted, exchanged, and stored. The communication field is one area that has seen considerable benefits. Fifteen years ago, a one minute commercial, international long distance call using an analogue network cost more than \$2.50. Today people can send an international, digital electronic message via the Internet for almost free. In the last twenty five years, civil telephone technology has experienced rapid improvements in telephone technology based on electrical wires, technologies based on wireless radio frequency (RF), MHz and GHz wireless systems, mobile analogue voice cellular telephones, and most recently, mobile digital cell phones with color imaging functions. These new technologies allow people to be interconnected worldwide at any time. The digital wireless communication technology makes information transfer more reliable and cheaper, especially for civil applications. These newly developed civil communication technologies would have been impossible if not for the advancements in microelectronics and packaging technologies.

The field of microelectronics has also had an impact on aerospace propulsion systems. Most aerospace engines today are equipped with microprocessors for local operational diagnostics and control. However, while the engine operation signals are processed by advanced microchips, the signal detection and transmission systems are still based on half century old technologies. The basic purpose of this article is to review the current status of electrical/electronic signal transmission technologies used in aerospace propulsion systems, and evaluate the potential of high temperature RF wireless data transmission technologies, especially in regard to aerospace engine health monitoring and ground testing.

2. Applications

In the sections below, high temperature wireless sensing and data transmission systems are discussed with respect to their applications towards intelligent aerospace engines, engine ground testing, as well utilization by advanced, space systems.

2.1 Engine Ground Testing

Both new and serviced turbine engines will undergo ground testing prior to flight testing. During engine ground tests, output electrical signals from various sensors are relayed to measuring devices and, in turn, measuring command signals from various instruments are sent to actuators on the engine. As a result, hundreds of wires are used to interconnect the engine and test equipments for both power and signal transfer. A very significant amount of the work during ground tests is due to the wiring. Figure 1 shows a picture of an on-site ground testing facility used for turbine engines research. Note the excessive wires and associated hardware shown in the picture.

If signal transmission between the engine (sensors and actuators) and ground testing instruments is exchanged through a RF wireless system, the ground testing could become much more stream lined due to reduced labor time and increased reliability in signal transmissions. Since some of these sensors and actuators are located in high

temperature areas, they will need high temperature RF (signal transmission) modules. Using a pressure sensor for combustion diagnoses as an example, the sensor will be subjected to temperatures of approximately 500 °C in the engine's compression section. A high temperature RF data transfer module would eliminate the massive and specialized wiring associated with such tests, and allow for efficient, wireless data transfer between sensor/actuator modules on the engine and ground instruments. Therefore, it is hoped that the next generation of intelligent engines, will no longer require massive wiring for signal interconnection during ground testing. A RF wireless ground data receiver will aim to collect all the signals from all engine sensor modules, while test instructions will be transmitted through the RF wireless system to all actuator modules on the engine.

The basic elements of a high temperature sensing and wireless data transmission module include high temperature microsensors, RF circuits, as well as high temperature RF packaging technologies. The definition of high temperature for these technologies is typically 500°C and higher. The technologies associated with these components and the technology readiness level will be reviewed in Section 3.

2.2 Intelligent Engine Technology

Currently, the pressure of an engine combustion chamber is measured *ex situ* by utilizing metal sampling-tubes, and the combustion products are detected at engine exhaust. The electric signals associated with these measurements are transmitted via long, massive wires. These wires are supported with even heavier metal hardware and fixtures. The wires used in elevated temperature areas, such as the one for ignition, are even bulkier. The wires and the associated hardware often fly with the engine, in turn leading to higher fuel cost and frequent maintenance. In order to improve both engine functionality and reliability, engine manufacturers intend to add even more sensors and actuators onto aerospace engines, which would imply additional wires and hardware, thus, higher fuel cost and more maintenance, or lower reliability.

NASA is developing the next generation of aerospace engines with much improved reliability and reduced exhaust emissions. Besides the mechanical improvements due to improvements in materials and design, an advanced electronic micro-system will be directly integrated onto the engine body to provide self-diagnosis and intelligent control of the engine. The hardware of this self-diagnosis and intelligent control system is composed of distributed sensing elements, signal and data transmission systems, a central signal/data processor, and control actuators. RF packaging and integration technologies suitable for high temperature environment operation are needed for this advanced engine control system.

Each high temperature sensing module includes micro-sensors, signal conditioning circuits, A/D converter, coding and RF modulation, and an antenna. The RF signals from sensing modules are transmitted to a central receiver, and following a demodulation and decoding process, the data will be compared with predefined control logic (model) for diagnosis. The packaging system for the sensing module has to be durable while also meeting RF signal standards. The results of the data analysis will then be converted to actuation signals by a central processor which is ideally located in a moderate temperature area. As a result, a 350°C packaging system should be sufficient for the central processor unit. The output control signals will then be transmitted from

the central processor unit to the distributed actuator modules on the engine through RF wireless transmission, in the same way as that transmitted from sensing unit to the central processor. The central processor has *in situ* operation information of the combustion process. This wireless data transfer system will dramatically improve engine functionality and reliability. First, this system provides real time engine combustion information such as chemical, pressure, temperature, acoustics, and flow distribution data. Second, these signals can be sent wirelessly to the central data processor unit while eliminating the need for excessive wiring. The wireless system would not only reduce the overall weight, but also improve the data exchange quality, efficiency, and reliability. Furthermore, more sensing and actuating units could be installed on the turbine engine allowing for more sophisticated diagnosis and control of the combustion process.

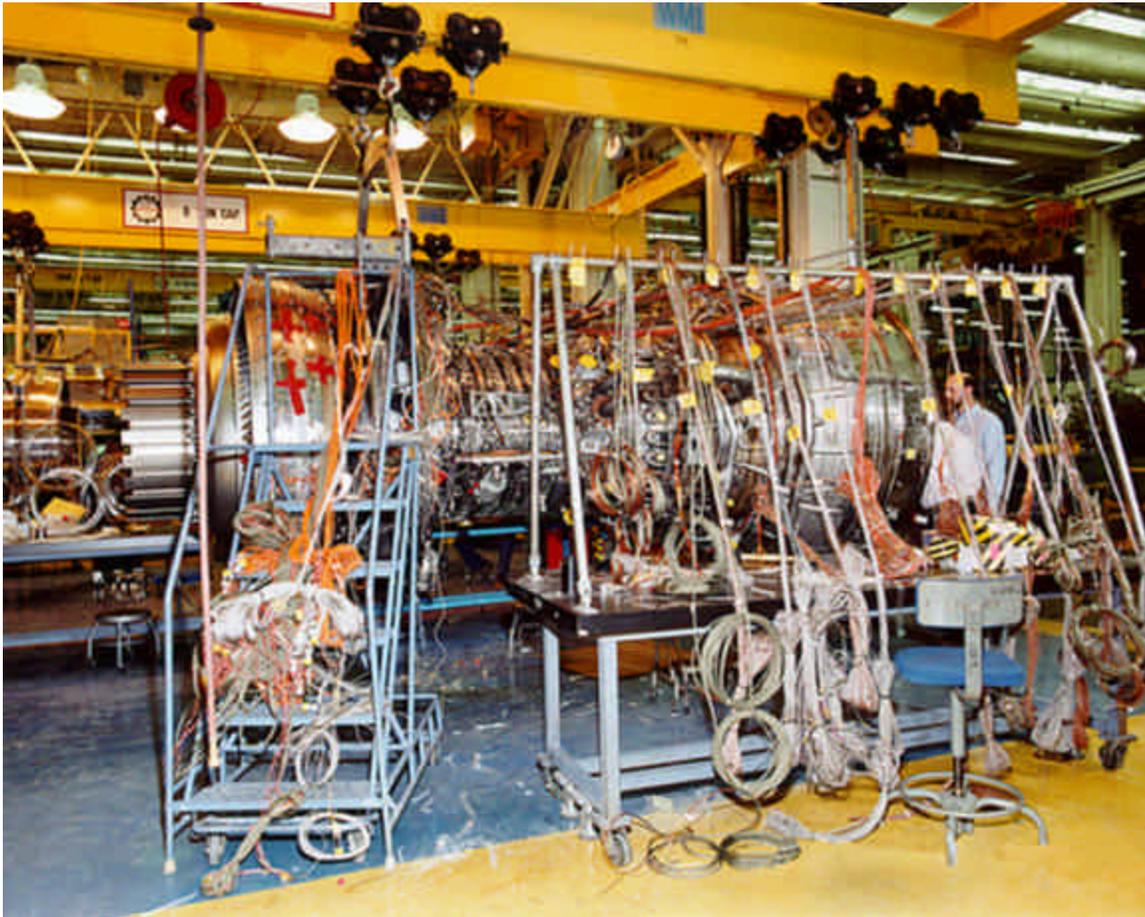


Figure 1: An on-site picture of an aerospace engine in ground test. Massive wires/cables and supporting hardware are used for interconnecting the sensing and actuating units on the engine with testing instruments.

NASA currently has numerous on-going aerospace engine technology programs and projects. Examples include the Ultra Efficient Engine Technology (UEET) Program, Next Generation Launch Technology (NGLT) Program, Intelligent Propulsion System Foundation Technologies (Propulsion 21) Program, and many more. An advanced, high

temperature wireless sensing and data transfer system would directly contribute to these aeronautic engine related programs/projects. Important contributions can also be gained by programs associated with inner-solar planets exploration.

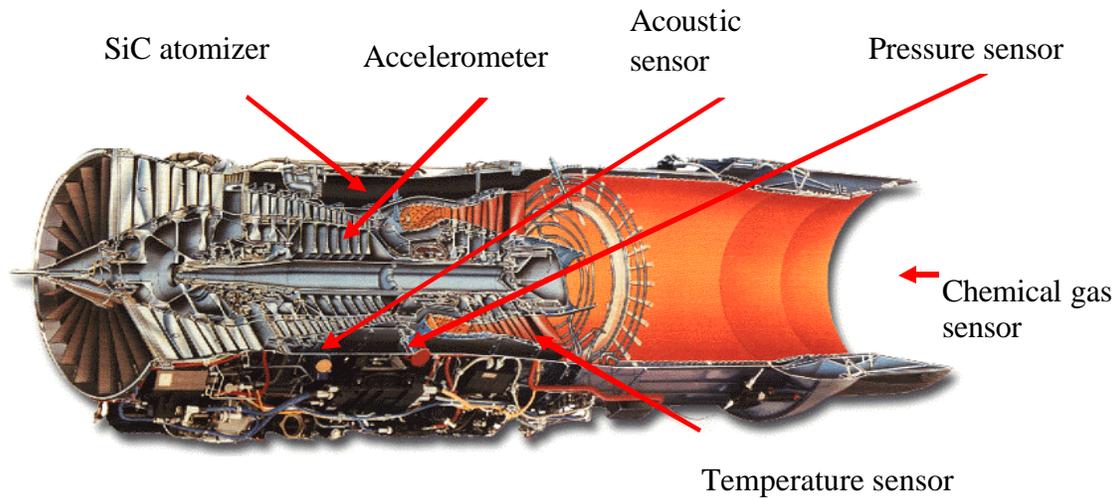


Figure 2: Aerospace turbo fan engine showing applications of high temperature sensors for advanced engine combustion diagnostics.

2.3 Inner-Solar System Exploration

Besides the applications in aerospace engine technologies, this high temperature RF wireless data transfer system also has applications in space exploration missions such as a Venus probe. The surface and atmosphere of Venus are extremely hot and corrosive. The surface temperature of Venus is approximately 462 °C. Typically, data collected from the surface of Venus will first be sent to a Venus orbiter through a RF data system. This data system must survive a high temperature (500°C) environment. The data system will also be needed for Venus “ground” communication if multiple landing probes are deployed. These landing probes would form a data network that collects various surface and atmospheric readings efficiently from the multiple locations to the orbiter.

3. Technology and Readiness

In this section, the technology of each technical component necessary for the high temperature sensing and wireless data system will be reviewed and analyzed.

3.1 High Temperature Electronic Devices

For the wireless data system to succeed for each of the applications discussed, there is a need for high temperature electronic devices. The expected environments for these sensing units have temperatures of 500°C and higher, which is beyond the operation temperature limits of Si and Si-on-Insulator (SOI) technologies. Conventional Si semiconductor electronic devices fail at elevated temperatures largely due to following

physical mechanisms: 1) High leakage current of reverse biased p-n junctions due to high intrinsic carriers concentration at high temperatures; 2) High leakage of reverse biased p-n junctions due to thermionic emissions; and 3) Forward current loss caused by lower carrier mobility due to higher scattering between charge carriers and crystal lattice at high temperatures. By replacing the semiconductor substrate with an insulator material, silicon-on-insulator (SOI) can dramatically reduce contact area of vertical p-n junctions, thus reducing the leakage. The SOI devices can operate up to $\sim 350^{\circ}\text{C}$, but that is still not sufficient for applications such as the compressor section of a turbine engine. A semiconductor material with a wide bandgap (WBG) can significantly reduce both intrinsic carrier concentration and thermionic leakage current of p-n junctions. therefore, allowing for operation at higher temperatures. WBG materials based high temperature electronic sensors and electronics are key elements of this high temperature wireless data transfer system. Silicon carbide (SiC) is one type of WBG materials that currently has a relatively mature single crystal growth process.

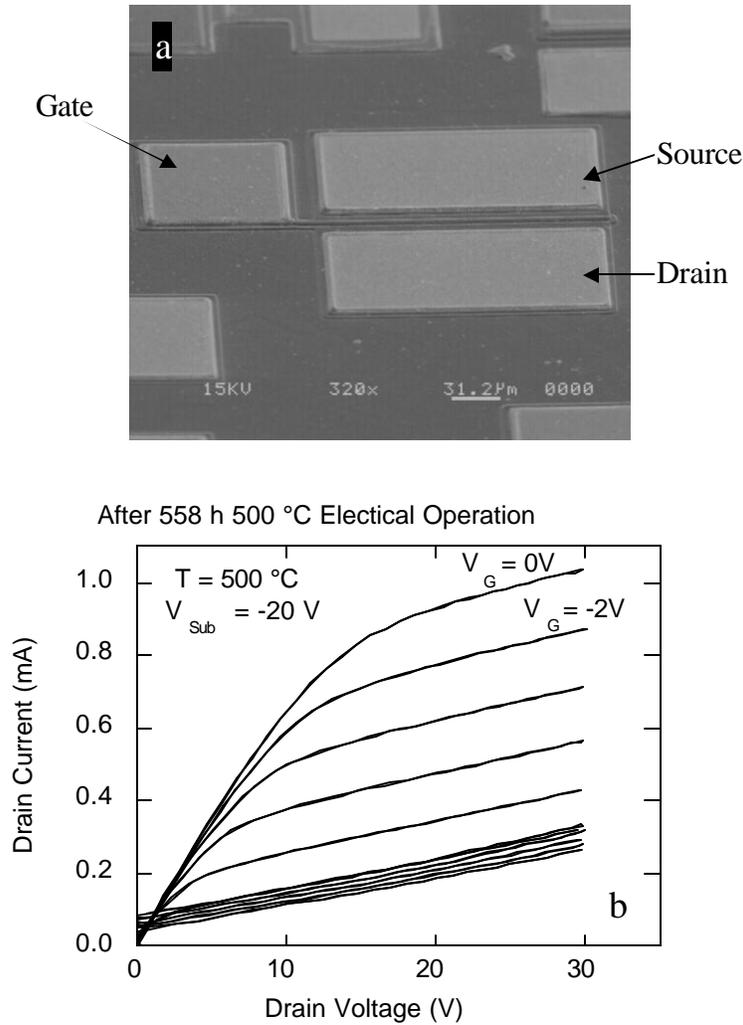


Figure 3: a) SEM micrograph of a SiC MESFET. b) Drain current vs. drain-source voltage at various gate biases of the SiC MESFET (tested at 500°C after 558 hours of continuous electrical operation in 500°C air ambient).

In addition to the aerospace field, high temperature electronic sensors, electronics, and wireless data transfer systems also have uses in oil field drilling and power industries. The future worldwide market is estimated to be in the billions of dollars over the next 10 years. Several institutions worldwide are currently involved in the development and commercialization of SiC and III-Nitride WBG materials based devices. Recently, a metal-semiconductor field effect transistor (MESFET) fabricated at NASA Glenn Research Center has been demonstrated at 500°C for over 2000 hours with continuous electrical operation (I-V sweeping with various gated DC biases) [Spry, 2004]. The MESFET was fabricated on a commercially purchased off-axis Si-face 6H-SiC epitaxial wafer. Figure 3a shows a SEM micrograph of the top view of the device. Figure 3b shows the IV data of the transistor in 500°C air after 500 hrs electrical testing/operation.

The RF for this wireless data transmission is allocated at approximately 800 MHz in order to have high efficiency, low interference with the environment, and reasonable size of emission/receiving antennas. As a result, high temperature high frequency electronic devices are essential to realizing these high temperature RF data transmission systems. Figure 4 shows a SiC Schottky diode based high temperature rectenna (rectifying antenna) developed at NASA Glenn. The rectenna assembly has been tested at high temperature and RF frequency [Ponchak, 2004].

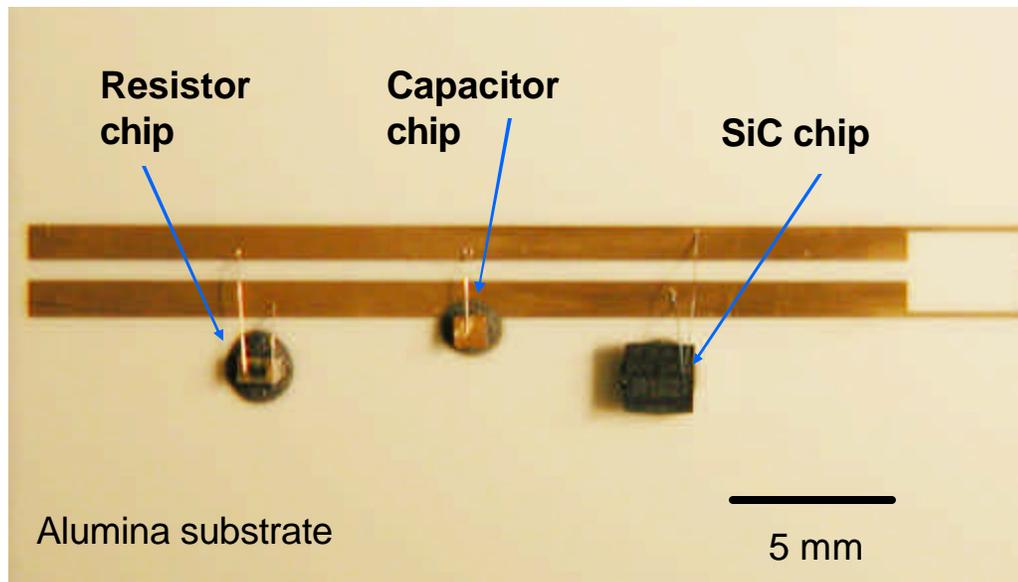


Figure 4: Optical picture of a SiC Schottky diode based high temperature rectenna that was designed and fabricated at NASA Glenn Research Center [Ponchak, 2004]. The high temperature packaging technologies developed at NASA GRC was used to assemble this test unit.

3.2 High Temperature Sensors

High temperature sensors needed for in situ diagnosis of aerospace engines include chemical gas (hydrocarbons, oxygen, CO, CO₂, and NO_x) sensors, pressure sensors, acoustic sensors, flow sensors, temperature sensors, and strain sensors. These

sensors are expected to operate in harsh engine environments with temperatures and pressure at and above 500°C and 500 psi, respectively. In addition the gasses are chemically corrosive.

Chemical gas sensors are ideally located in both combustion and exhaust areas to characterize the combustion chemical processes. This is done by measuring both intermediate and final (combustion) products in order to adjust injected fuel/air ratio, fuel/air flow rate, and distributions. Optimized fuel/air ratios and spatial distributions can significantly improve the fuel efficiency while reducing the exhaust emissions, such as CO, CO₂, and NO_x. In addition, optimized engine operation will improve the overall engine reliability and reduce the maintenance work load. Figure 5 shows a SiC high temperature hydrocarbon sensor for emission detection. Figure 6 shows rake sampling system at the outlet of the JT-12 jet engine.

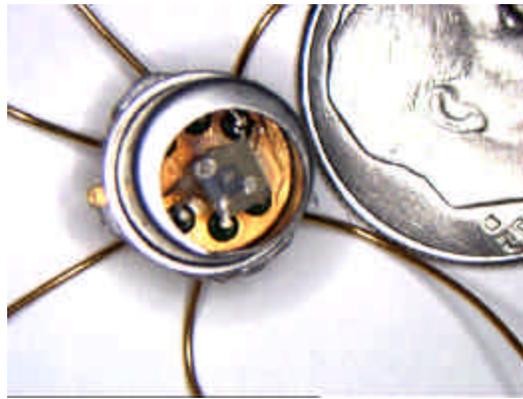


Figure 5: SiC hydrocarbon sensor for emission detection.

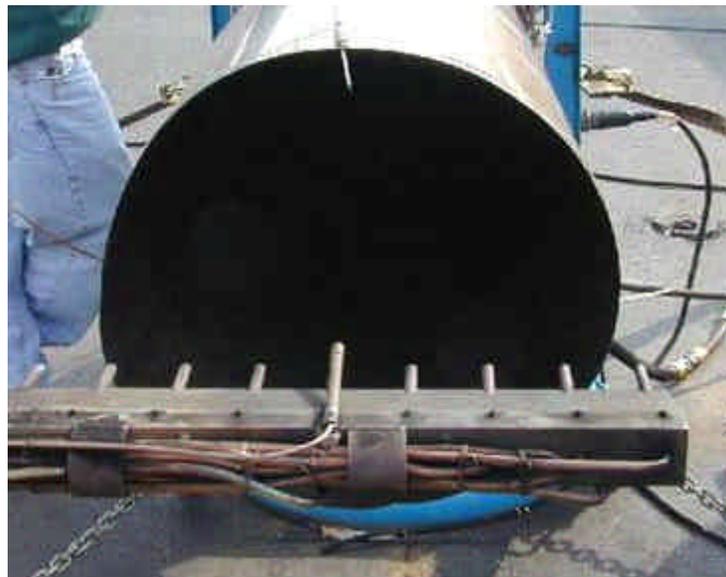


Figure 6: Rake sampling system at the outlet of the JT-12 jet engine.

Pressure, acoustic, temperature, and other physical sensors such as stress/strain sensors are used to physically characterize the combustion process by measuring the physical parameters and their distributions in real time during engine operation. The measured information dramatically increases the engineer's knowledge of both the combustion process and the performance of engine components. Ultimately, the information will allow engine developers to optimize the engine design and operation, especially, during take off and landing. Figure 7 shows a multi functional, high temperature, thin-film physical sensor developed at the NASA Glenn Research Center for measuring strain, heat flux, and flow [Wrbanek and Fralick *et al*, 2001].

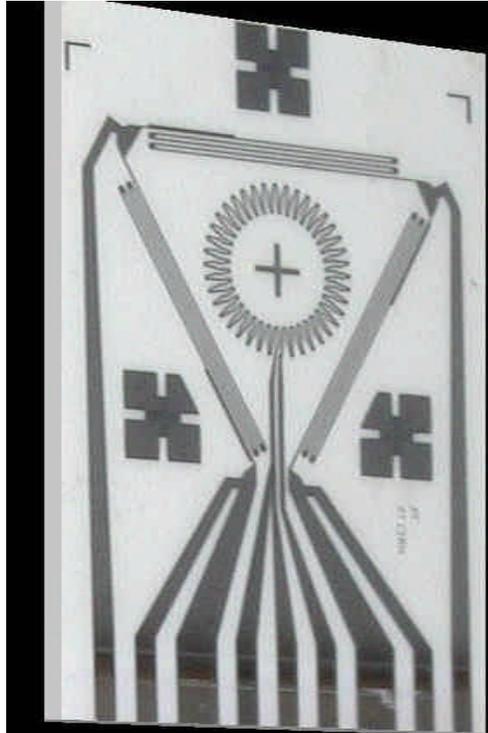


Figure 7: Multi functional high temperature thin-film physical sensor developed at NASA Glenn Research Center for strain, heat flux, flow, and temperature measurements.

3.3 High Temperature Packaging Technologies

Packaging technology which is capable of operating in a high temperature environment is essential to the wireless data system. Innovative chip level packaging (also called level one packaging), printed circuit board packaging (level two), and instrument (unit) packaging (level three) are all needed for the data system. The level one packaging provides single or multi device chip(s) with macro-level protection/insulation and electromagnetic, mechanical, thermal, and chemical/biological interconnections. Note that following level-one packaging, the device chips are ready for handling and macro utilization. Printed circuit board (PCB) level packaging provides interconnections between the packaged devices and discrete passives. It is considered

level two packaging. Next, instrument level packaging provides interconnections between PCBs and other units and makes it a functioning unit. As in the case of sensing/actuating modules, it is considered level three packaging. All three levels have to be durable in regard to high temperature environments, and also be compatible to RF standards.

High temperature device packaging is a relatively new field, especially for devices that operate at temperatures up to 500 - 600°C. Researchers at the NASA Glenn Research Center have demonstrated high temperature packaging systems (500 °C applications) composed of ceramic substrates, such as AlN and Al₂O₃, and precious metal thick-film metallization. Based on these materials, packaging systems composed of chip-level packages and printed circuit boards (PCB) have been developed. A multi-function sensor packaging module for high temperature sensors is currently being validated under NASA's Electronic Parts and Packaging (NEPP) Program. Electrically conductive die-attach materials, based on Au and Pt thick-film materials, have also been tested with SiC high temperature devices such as Schottky diodes and MESFETs. The MESFET shown in Figure 3a was tested using one of these packaging systems at 500°C. A 96% Al₂O₃ substrate and Au thick-film metallization [Chen, 2004] were used as the packaging framework. The SiC die was attached to the Au thick-film metallized packaging substrate using an in-house-developed, Pt-based electrically conductive die-attach material, that was specifically designed for the Pt thin-film capped ohmic contact metallization on the backside of the SiC chip. This die attach material provides a relatively low cure temperature of 500°C. As a result, the device was not exposed to any higher temperatures beyond the testing/operation environment during the die-attach process. 1 mil diameter Au (98%) wires were used to electrically connect the device to the metallization traces on the alumina substrate using thermo-sonic bonding. The I-V characteristics of the MESFET device after 558 hours of continuous testing/operation at 500°C are shown in Figure 3b. The high temperature testing lasted over 2000 hr, and the packaging system remained stable.

SiC Schottky diode chips have also been tested using the above described packaging system. The diode was attached to a ceramic (96% alumina) substrate using selected Au thick-film materials. An optimized thick film die-attach process for SiC devices resulted in a low-resistance, conductive die-attach that is very often required for devices with backside electrical contact. A SiC test die, with an Au/Ni contact on the back side, was attached to a ceramic substrate using optimized, two-step Au thick-film processing [Chen *et al.*, 2000b]. An Au thick film layer was first screen-printed on the substrate and cured at 850°C using the standard process. The SiC die was then attached to the cured thick-film pattern with a subsequent layer of Au thick film. Following a drying process, the die-attached assembly was processed at a lower final curing temperature, it prevents the attached semiconductor chip from being exposed to temperatures above the ultimate operation temperature of SiC devices (600°C) during the die-attach process. A thin Au wire was bonded to the top of the Au thin-film metallization area covered with an Au thick-film over-layer by a thermal-compression bonding technique. The thick-film material was also used to reinforce the top Au thin film for better wire bonding. The Au thin-film metallization area was coated with a thick film then dried at 150°C for 10 minutes. The thick film on the device top was cured during the final die-attach process (at 600°C).

The attached SiC test diode was characterized by current - voltage (I-V) measurements at both room temperature and 500°C after various heating times at 500°C. A minimum dynamic resistance (dV/dI) under forward bias (deduced from the I-V curve) was used to monitor the resistance stability of the die-attach. This dynamic resistance includes the forward dynamic resistance of the AuTi-SiC interface, SiC wafer bulk resistance, the die-attach materials/ interfaces resistance, bonded wire resistance and the test leads resistance in series. The resistance contributed from test leads and bonded wire were measured independently and subtracted. The attached device was first characterized by I-V measurements at room temperature. The device exhibited rectifying behavior, and the minimum dynamic resistance after subtracting test-leads/bond-wire resistance (which also applies to all the following discussion) measured under forward bias was approximately 2.6 Ω . The temperature was then ramped up to 500°C (in air) and the diode was characterized *in situ* periodically by I-V measurement for approximately 1000 hours. During the first 70 hours at 500°C, the minimum dynamic resistance under forward bias increased slightly from 3.3 Ω to 3.8 Ω . After that, the minimum dynamic resistance decreased slightly and remained at an average of 3.1 Ω . The diode was then cooled to room temperature and characterized again. The minimum forward dynamic resistance measured at room temperature was 3.3 Ω . The minimum dynamic resistance of the attached diode remained comparatively low over the entire duration of the test and the entire temperature range, indicating a low and relatively stable die-attach resistance. The complete packaging system, including chip-level packages and a printed circuit board (PCB) developed at NASA GRC, are still being subjected to further reliability evaluations in various thermal, mechanical, and radiation environments.

Besides the high temperature device packaging technologies developed at NASA Glenn intended for 500 – 600°C applications, Honeywell developed and commercialized a packaging technology for their SOI devices and circuits including RF circuits. These SOI devices are designed for operation at temperatures up to 250-300°C. At 300°C, these devices/circuits continue to operate, but with a different rating. The packaging system is based on a ceramic substrate. The packaging system is suitable for the central data processing unit that is located off the engine combustion chamber. In addition to this commercialized 300°C packaging technology, high temperature packaging technologies for specific sensors and devices such as high temperature pressure sensor and hydrocarbon sensors are being developed and commercialized by the private sector. Sienna Technology and Kulite Semiconductor are working with NASA Glenn in developing and commercializing SiC high temperature MEMS pressure sensors with packaging for aerospace applications in a temperature range of 350 – 600°C [Ned *et al*, 2004 and Savrun *et al* 2004]. Makel Engineering is working with NASA Glenn on a high temperature chemical gas sensor [Hunter, 2004]. University of Nevada is collaborating with NASA on a high temperature MEMS acoustic sensor and packaging for engine combustion process characterization.

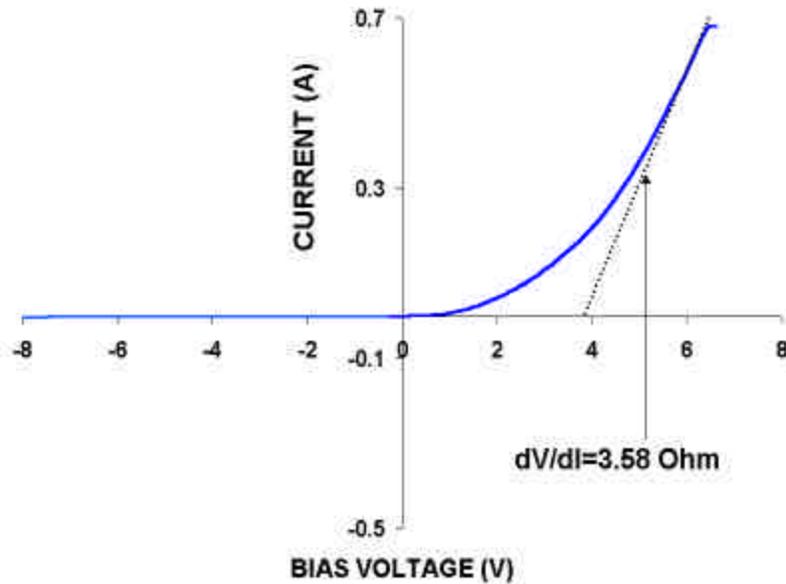


Figure 8: Current-voltage (I-V) curve of a SiC Schottky diode measured at 500°C after being tested in 500°C air ambient for 1000 hrs. The device chip was attached to a Au metallized ceramic substrate using Au thick-film material. Au wire and thermal-sonic wirebond was used to connect the top metallization of the diode with the metallization trace on the packaging substrate.

In order to minimize the dimensions of the RF emission antenna, the signal modulation and emission circuits of a wireless sensing module operate at approximately 800 MHz RF frequency. Therefore, the packaging for these wireless sensing units needs to be validated for both high temperature durability and high frequency reliability. This high temperature RF packaging technology is not yet commercially available at this stage. NASA Glenn Research Center has been developing and validating this technology for the high temperature wireless data transmission system. The packaging system is needed for both application and commercialization of the data system. A validated high temperature RF packaging technology is also needed, at this point, for long-term testing of high temperature RF devices. The packaging material/subcomponents to be validated for high temperature RF operation include ceramic substrates (such as aluminum oxides and aluminum nitride), die-attach material, electrical interconnections such as wire-bonding, and RF design. The thermal and electric properties of the substrate materials at high temperature and radio frequency may need to be characterized for precise RF design.

Figure 4 shows a high temperature RF rectenna (the function of a rectenna is to receive the RF signal and converting it to a DC output) assembled on an alumina substrate. The substrate was Au thin-film metallized. The SiC Schottky diode as well as the passive components were all attached onto the substrate using a high temperature conductive die-attach material. The conductive die-attach provides an electrical connection to the backside contact of the device chip. Heavily doped 1 mil Au wires were used to interconnect the components to the substrate. The circuit is currently being

characterized at NASA Glenn Research Center for high temperature RF applications [Ponchak, 2004].

4. Commercial Interests

In this section, the commercial interests of two major aerospace engine manufactures, GE Engine and Pratt and Whitney, concerning high temperature wireless sensing and data transmission systems are summarized.

4.1 Aerospace Engine and Sensing Technology

In order to better understand the technologies currently used for sensing and electrical signal transmission for aerospace engines, we participated in a tour of a major modern aerospace engine testing facility. This tour helped us to update our knowledge of modern aircraft engines, and visualize the sensing and wiring systems utilized on various advanced aircraft engines. Current generation aircraft engines, including most advanced large size high power turbine engines, sensing elements for combustion monitoring and characterization are very often located at relatively remote positions with respect to the combustion chamber because of lack of high temperature sensors and packaging technology. For example, pressure signals are transmitted mechanically through stainless-steel sampling tubes to off-site sensors for measuring. Signal processing and control boxes, equipped with a microprocessor, are usually located in a relatively low temperature region, while all signals are transmitted by electrical wires. Electrical cables in high temperature areas are equipped with cooling systems for temperature control. In its current format, the wires, inter-connectors, and supporting hardware/fixtures are quite bulky. It is apparent that high temperature wireless sensing technology could save hundreds of pounds in weight directly related to the engine. During maintenance and ground testing, these wires/cables have to be replaced with ones to be utilized by a particular test. Overall, the utilization of microelectronics technology on advanced aircraft engines is not very high. A high temperature electronic sensing and wireless data transmission system would dramatically improve the sensing and control capability of these mechanically advanced aircraft engine. Concerning ground testing, a high temperature wireless sensing and wireless data transmission system would greatly improve efficiency and capability.

4.2 Engine Research

Major aerospace engine manufacturers recognize high temperature wireless sensing of pressure, temperature, strain, and chemical species as an essential technology in need of development for the new generation of aerospace engines. The capability to *in situ* measure these combustion parameters in real time would dramatically expand an engineer's knowledge of both engine operation and combustion processes, especially, those physical parameters directly applied to the engine's rotating blades and disks. Major aerospace engine manufacturers expressed strong interests in high temperature wireless sensing and data transmission technologies including high temperature RF packaging which is currently under development at NASA GRC. Efficiency and

reliability of aircraft engines are dominant factors that directly relate to the overall economy and safety of an aircraft. Many aircraft flight accidents have been associated to sudden engine failure. A sophisticated high temperature wireless sensing and data transmission system would provide *in situ* and real-time thermal, mechanical, and chemical operation data of various components in an engine.

5. High Temperature Sensor and Electronics Programs at GRC

NASA has significant interests and efforts in high temperature electronics and sensor research. This is especially true at the NASA Glenn Research Center. In FY 2003, NASA JPL organized a Harsh Environment Electronics Conference with focus being on the needs and availability of high temperature, extreme low temperature, and radiation resistant electronics and sensor technologies for NASA space exploration missions. Currently, NASA's Ultra Efficient Engine Technology project (UEET) supports the research and development of high temperature wireless data transmission systems (this includes high temperature, RF packaging technologies) at NASA GRC. Examples of high temperature sensors and electronics related programs/projects at GRC include chemical sensors, fire detection systems, fuel leak detection projects, Propulsion 21st Century Program, as well as GRC IR&D programs. These programs/projects support high temperature sensors and electronics related research efforts in single crystal SiC (epilayer) material growth, chemical gas sensors [Hunter, 2004], SiC electronic devices [Neudeck, 2004], SiC MEMS pressure [Okojie, 2001 and Beheim, 2001] and acoustic sensors, SiC etching processes [Beheim, 2004], thin-film high temperature flow sensors, strain sensors, temperature sensors [Wrbanek and Fralick *et al*, 2001], and high temperature device packaging [Chen, 2004].

6. Conclusions

A high temperature wireless sensing and data transmission system including packaging technology is a key component required for NASA and the aerospace industry to develop highly reliable, efficient, and clean aerospace engines. An *in situ* sensing and data transmission system would allow more sophisticated monitoring of the combustion process as well as the general performance of various engine components, therefore, improving the engine reliability and overall vehicle health. A high temperature wireless data transmission system would eliminate excessive wiring and the associated support hardware while allowing for schemes to improve the engine combustion efficiency. This is especially true during the take-off phase, where the engine could attain improved monitoring and control due to an advanced electronic system. Enabled by high temperature electronic control systems, the engine fuel efficiency could be improved, and the exhaust emissions significantly reduced. Implementing a high temperature wireless data system will also significantly improve the efficiency of engine ground tests by eliminating the massive wiring effort needed for communication between the engine and the testing instrumentation. Furthermore, in regard to general space exploration, a 500 °C operable wireless data transmission system is also an enabling technology for NASA space programs associated with the exploration of inner solar planets, (e.g., Venus). Lastly, a validated high temperature, RF device packaging technology is vital for the

successful implementation of any wireless sensing and data transfer system associated with advanced aerospace engines.

The NASA Glenn Research Center, together with industry and university partners, demonstrated ceramic substrate based high temperature packaging material systems and various sensor packaging technologies. Validation of packaging technologies for high temperature and radio frequency applications still needs to be carried out in order to implement a high temperature wireless sensing and data transmission system.

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References

Beheim, G., Ned, A.A., Masheeb, F., Kurtz, A.D., and Wolff, J.M. (2001) "Dynamic Pressure Measurements Using Silicon Carbide Transducers," *19th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF '01)*, Cleveland, Ohio, August 27-30, 2001.

Beheim, G.M. and Evans, L. (2004) "Deep Reactive Ion Etching for Bulk Micromachining of Silicon Carbide," in *the CRC MEMS Handbook*, CRC Press, Boca Raton, LA.

Chen, L.-Y., Hunter, G.W., and Neudeck, P.G. (2000) "Silicon Carbide Die attach Scheme for 500°C Operation," in *Proceedings of MRS 2000 Spring Meeting – Wide Bandgap Electronics Devices (Symp. T)*, April 10-14, San Francisco, CA,.

Chen, L.-Y. and Lei, J.-F. (2004) "Packaging of Harsh-Environment MEMS Devices," in *the MEMS Handbook*, August, CRC Press, Boca Raton.

Hunter, G.W. , Neudeck, P., Thomas, V., Chen, L., Liu, C.C., Ward, B., Wu, Q.H., Makel, D., Dutta, P., Frank, M., Trimbol, J., Fulkerson, M., and Patton, B. (2002) "Development of Chemical Sensor Arrays for Harsh Environments and Aerospace Applications," in *Proceedings of IEEE Sensors 2002*, June 12-14, Orlando, FL.

Hunter, G.W., Liu, C.C., and Makel, D.B. (2004) "Microfabricated Chemical Sensors for Aerospace Applications," Chapter 27, *the CRC MEMS Handbook*, CRC Press, Boca Roton, LA.

Hunter, G.W., Neudeck, P.G., Xu, J., Lukco, D., Trunek, A., Artale, M., Lampard, P., Androjna, D., Makel, D., Ward, B., and Liu, C.C. (2004) "Development of SiC-based Gas

Sensors for Aerospace Applications,” in *the Proceedings MRS Spring Meeting*, April 12-16, San Francisco, CA.

Kurtz, A.D., Kochman, B., Ned, A.A. (2004) “High Temperature SiC Beam (Pressure) Sensor with Frequency Output,” in *the Proceedings of 7th International High Temperature Electronics Conference (7th HiTEC)*, May 17-20, Santa Fe, NM.

Moore, G.E. (1965) “Cramming More Components into Integrated Circuits,” *Electronics*, Vol. 38, 8, April 19.

Ned, A.A., Kurtz, A.D., Epstein, A.H. (2004) “Ultra High Temperature, Miniature, SOI Sensors for Extreme Environments,” in *the Proceedings of 7th International High Temperature Electronics Conference (7th HiTEC)*, May 17-20, Santa Fe, NM.

Neudeck, P.G., Beheim, G.M., and Salupo, C.S. (2000) “600C Logic Gates using Silicon Carbide JFETs,” on *Proceedings of Government Microcircuit Applications Conference*, Anaheim, CA.

Neudeck, P.G., Okojie, R.S., and Chen, L.-Y. (2002) “High-Temperature Electronics – A role for Wide Bandgap Semiconductors?” in *the Proceedings of the IEEE, Special Issue (June) on Wide Bandgap Semiconductor Devices*.

Okojie, R.S., Beheim, G.M., Saad, G.J., and Savrun, E. (2001) “Characteristics of Hermetic 6H-SiC Pressure Sensor at 600°C,” in *Proceedings of AIAA Space 2001 Conference and Exposition (AIAA Paper No. 2001-4652)*, August 28-30, Albuquerque, NM.

Okojie, R.S. (2004) “Fabrication and Characterization of Single-Crystal Silicon Carbide MEMS,” Chapter 23, *CRC MEMS Handbook*, CRC Press, Boca Raton, LA.

Ponchak, G., Jordon, J.L., Downey, A.N., and Schwartz, Z. (2004) “2.45 GHz Rectenna Designed for Wireless Sensors Operating at 500°C,” in *the Proceedings of 7th International High Temperature Electronics Conference (7th HiTEC)*, May 17-20, Santa Fe, NM.

Savrun, E., Nguyen, V., Okojie, R., and Blaha, C. (2004), “Accelerated Stress Testing of MEMS-DCA Pressure Transducers,” in *the Proceedings of 7th International High Temperature Electronics Conference (7th HiTEC)*, May 17-20, Santa Fe, NM.

Spry, D., Neudeck, P., Okojie, R., Chen, L.-Y., Beheim, G., Meredith, R. (2004), “Electrical Operation of 6H-SiC MESFET at 500°C for 500 Hours in Air Ambient,” in *the Proceedings of 7th International High Temperature Electronics Conference (7th HiTEC)*, May 17-20, Santa Fe, NM.

Trew, R.J. (2002) “SiC and GaN Transistors – Is There One Winner for Microwave Power Applications?” in the *Proceedings of the IEEE, Special Issue (June) on Wide Bandgap Semiconductor Devices*.

Wrbanek, J.D., Fralick, G.C., Martin, L.C., and Blaha, C.A. (2001) “A Thin Film Multifunction Sensor for Harsh Environments” in the Proceedings of 37th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Salt Lake City, Utah, July 8-11, 2001. AIAA paper No. 2001-3315.

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