Survey Report of Current Status of High Temperature Microdevices Packaging

- For NEPP program, September 2004

Liangyu Chen, OAI/NASA Glenn Research Center

1. Brief description of the technology

Wide band-gap semiconductor materials such silicon carbide (SiC), gallium nitride (GaN), and diamond (C) based electronic devices may operate at temperatures above the high temperature limit of silicon technology. Among these wide band gap materials, single crystal SiC is the most mature material at this stage. SiC has such excellent physical and chemical material properties that SiC microsystems, including MEMS sensors/actuators and signal conditioning/computing electronics, have been demonstrated at temperatures in excess of 600^{o}C. Microsystems that can operate in harsh environments, such as high temperature (~600^{o}C), are necessary for many space and aeronautic applications. Sensors and electronics for space missions to the inner solar system or combustion/emission control sensors/ electronics located in an aeronautical engine environment are desirable. For example, the Propulsion Instrumentation Working Group (PIWG), a working group composed of government labs and engine manufactures, suggested that the minimum environmental temperature requirement for sensors operating in a warm section of turbine engine (fan area) is 500^{o}C (http://www.piwg.org/PDF/DynamicPressure.pdf). As a point of reference, SiC MEMS and semiconductor devices fabricated at NASA GRC have been demonstrated operable at temperatures as high as 600^{o}C.

In order to test and commercialize high temperature microsystem technology, packaging technology is essential. Currently, most high temperature MEMS sensors/actuators and electronics have been tested only in laboratory environments for short term evaluation and demonstration. Most commercially available products have not been rated for long term high temperature operation. The major reason for this is that packaging technology for high temperature microsystems operability at and over 500^{o}C has not been completely evaluated/validated. Validating packaging technologies for SiC sensors/actuators and electronics is an immediate need for many NASA missions, and therefore, is one of the current tasks of the NASA Electronic Parts and Packaging Program. This article reports the survey results of the current status of high temperature micro-devices packaging.

2. High Temperature Packaging Technology

High temperature devices and packaging technologies, products, and efforts currently existing at various institutions are briefly summarized in this section.

NASA GRC: Researchers at NASA Glenn Research Center (GRC) have developed prototype packages for high-temperature microsystems using ceramic substrates (aluminum nitride and aluminum oxides) and gold (Au) thick-film metallization. Packaging sub-components, which include a thick-film metallization-based wirebond inter-connection system and a Au thick-film based low-electrical-resistance SiC die-attachment scheme, have been tested at temperatures up to 500 °C. The interconnection system composed of Au thick-film printed wire and 1-mil Au wire bonds was tested in 500 °C oxidizing air with and without 50-mA direct current for over 5000 hr. This electrical interconnection system was also tested in an extremely dynamic thermal environment to assess thermal reliability. A SiC Schottky diode with Ni/Au ohmic contacts was packaged using these technologies. The packaged diode was tested at 500°C for over 1000 hrs. Figure 1 shows the current-voltage (I–V) curve of a SiC high-temperature diode measured in oxidizing air at 500°C after 1000 hr (Chen, 2000 and Chen, 2002). The diode was attached to the substrate using Au thick-film material.

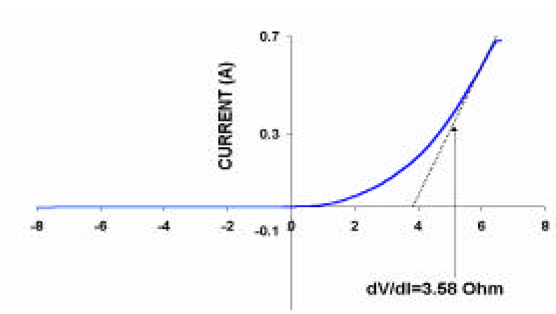

Figure 1: I-V curve of a SiC Schottky diode measured in 500°C oxidizing environment after 1000 hrs at 500°C.

Based on these material systems, low power 8-pin chip-level packages for SiC devices have been fabricated. Component level testing indicated that the electrical resistance of 96% Al_2O_3 substrate and Au thick-film based electrical interconnection system demonstrated low (2.5 times the room-temperature resistance of the Au conductor) and stable electrical resistance (decreased less than 5 percent during the 5000-hr continuous test). Also as required, the electrical isolation impedance between two neighboring printed wires (of the package shown in Figure 2) that were not electrically joined by a wire bond remained high (>0.4 GΩ) at 500 °C in air. Gold ribbon-bond samples (1 mil by 2 mil) survived 500 thermal cycles between room temperature and 500 °C (with 50 mA direct current), at the rate of 53 °C/min, without electrical failure. An attached SiC diode demonstrated low (< 3.8 Ω-mm^2) and relatively consistent forward resistance from room temperature to 500 °C. These results indicate that the prototype package and the compatible die-attach scheme meet the initial design standards for low-power, long-term, and high-temperature operation. Printed circuit boards to be used to interconnect these chip-level packages and passive components have also been developed. Figure 2 shows the chip level packages of AlN and aluminum oxides. Figure 3 shows two kinds of Al_2O_3 printed circuit boards to be used to characterize eight-pin low-power packages and devices at temperatures up to 500°C.

The Sensor and Electronics Branch at NASA GRC has recently demonstrated a 6H-SiC metal-semiconductor field effect transistor (MESFET) (Neudeck et al, 2004) with triple layer ohmic contacts (Okojie, 2000) for high temperature operation. The device was designed and fabricated at NASA Glenn under the Glennan Microsystems Initiative (GMI) and the High Temperature Wireless Telemetry task of Ultra Efficient Engine Technology (UEET) project. In order to test this device, a platinum (Pt) based die attach material has been developed for the Pt thin-film capped ohmic contact on the backside of the device chip. This die attach material has the following features: high electrical conductivity, relatively low processing (curing) temperature (500°C), and material compatibility with Pt capping layer. Heavily doped Au wire was used to electrically interconnect the Pt capped ohmic contacts on the device chip and the packaging substrate.

This packaged MESFET was electrically tested (I-V sweeping) continuously at 500°C in an oxidizing air ambient for over 2000 hrs facilitated by these in-house developed packaging systems. The overall transistor parameters changed less than 10% in the first 500 hrs of continuous electrical testing (I-V sweeping with gate bias) at 500°C indicating satisfactory performance of the packaging system. Figure 4 shows the I-V curves of the packaged MESFET measured at various gate biases at 500°C. The high temperature packaging technology that NASA GRC is testing and validating is not only limited to SiC high temperature sensors/devices; they are also useful to GaN and SOI (silicon on insulators) technologies.

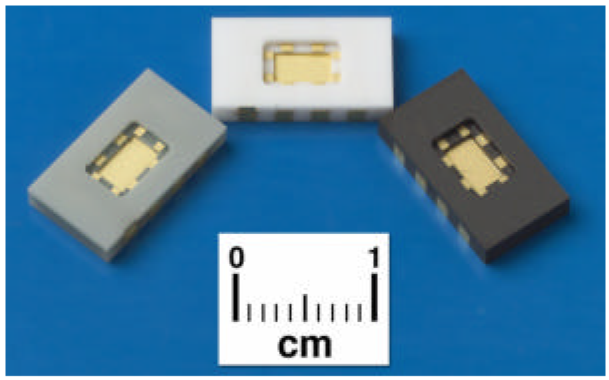

Figure 2: AlN and Al_2O_3 based chip level packages for SiC devices.

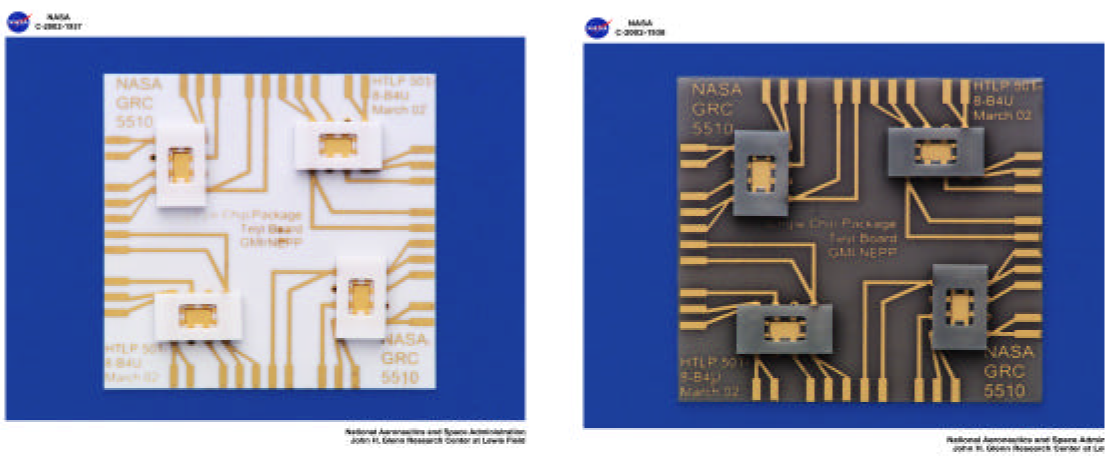

Figure 3: Aluminum oxide and aluminum nitride high temperature 8-pin chip level packages and printed circuit boards.

NASA GRC is also working on a multi-functional packaging module for SiC high temperature sensors. This spark plug type packaging is basically designed for measurement of acoustic pressure in aerospace engine compartment with capability of accommodation of other sensors and signal conditioning electronics.

In addition to the efforts in electronic devices and packaging NASA GRC has significant research efforts in high temperature electronic sensors, such as chemical gas (hydrogen, hydrocarbons, NO_X, CO, and CO_2) sensors, pressure sensors, and acoustic sensors. A variety of gas sensor technologies have been developed which is operational at high temperatures (Hunter, 2001). For example, SiC Schottky diode gas sensors have been developed and tested/demonstrated for detection of hydrogen and hydrocarbons at 450^oC with very high (~ ppm) detection sensitivity (Hunter, 2002). These gas sensors have application in rocket fuel leak detection, engine emission control, and airplane fire detection. Figure 5a shows responses of a packaged Schottky diode gas sensor, as a part of a high temperature electronic nose system, to various hydrocarbon concentrations at high temperature with parallel monitoring of oxygen and NO_X concentrations. Figure 5b shows a picture of a packaged high temperature SiC Schottky diode hydrocarbon sensors and thin-film resistive sensors in a ceramic package resulting from high temperature electronic nose work. Recently, atomic flat 4H-SiC epi-surfaces have been used to improve the thermal stability of metal/SiC Schottky diode sensors at high temperatures showing the potential of these devices fabricated with improved SiC material surfaces (Hunter, 2004). A SiC Schottky diode sensor fabricated on standard material was also tested as part of a "Lick and Stick" leak sensor system. The packaged sensor, while operated at high temperatures, was packaged in a unit operating at near room temperatures. Microfabricated electrochemical cell sensors for detection of CO_2 have been demonstrated at temperatures at 600^oC (Hunter, 2002; Xu, 2004). Figure 6 shows the sensor response to CO_2 at various concentration levels. Makel Engineering Inc., has worked with NASA GRC to package and integrate these chemical gas sensors with signal conditioning electronics.

SiC MEMS piezoresistive pressure sensors designed and developed at GRC have been demonstrated at temperatures up to 600^oC (Okojie, 2001, and Beheim, 2001). These high temperature pressure sensors will be used *in situ* to characterize the engine combustion process in real time. High temperature pressure sensors also have many commercial applications, such as the automobile industry. Figure 7 shows a picture of a packaged SiC high temperature pressure sensor. The enabling technologies for fabricating SiC high temperature pressure sensors include deep reactive ion etching (deep RIE) of SiC bulk material (Beheim, 2002). Major issues associated with current pressure sensor packaging include the packaging thermal effects on the pressure measurement during environment temperature changes. In recent years, NASA GRC has collaborated with Sienna Technologies and Kulite Semiconductor Products with respect to pressure sensor and packaging research and development efforts.

NASA GRC has significant efforts in basic SiC electronic materials research covering the following areas: epilayer material growth, atomically flat epi-surface preparation, crystal structure transformation, doping concentration control, nano SiC materials, high temperature passivation, and deep reactive ion etching. These fundamental efforts have been supporting the high temperature sensors and devices developments at GRC.

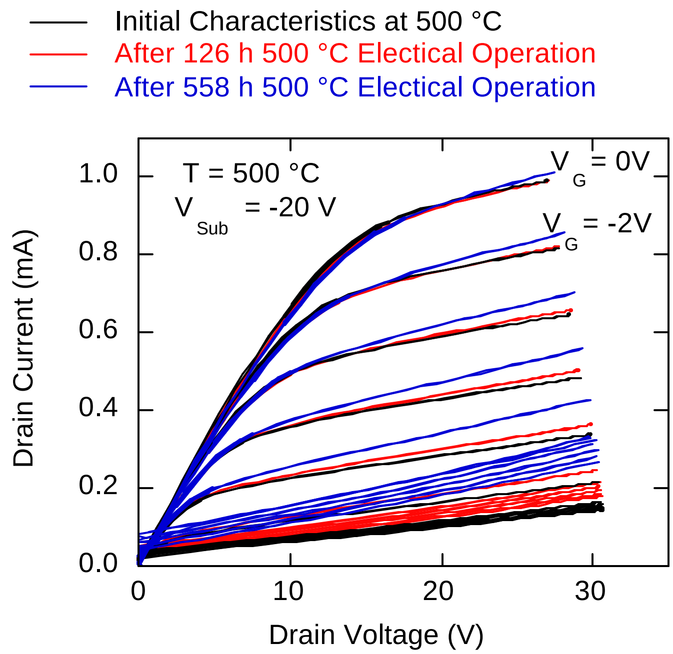

Figure 4: I-V curves of packaged SiC MESFET at various gate biases for V_{Sub} = -20 V.

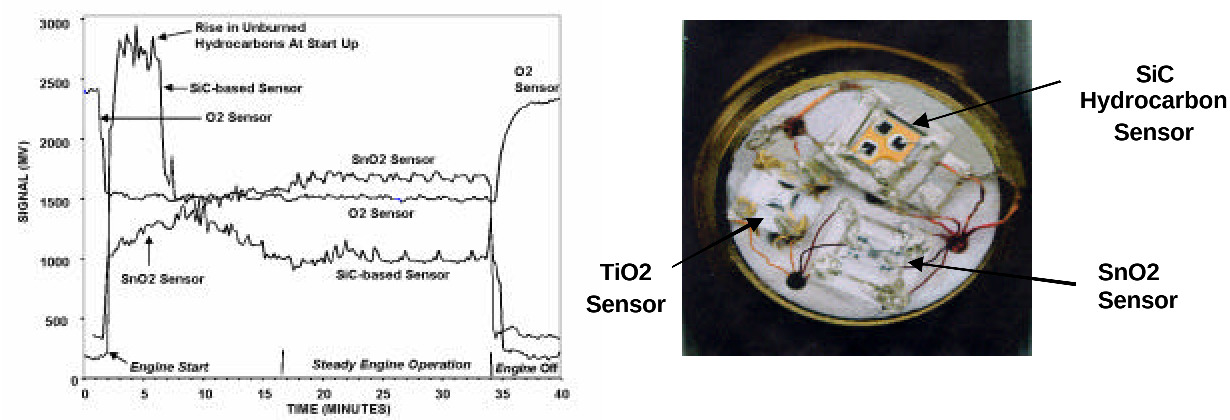

Figure 5: a) The response of a packaged sensor array composed of a tin oxide based sensor (doped for NO_x sensitivity), an oxygen sensor, and a SiC-based hydrocarbon sensor in an engine environment. b) Optical micrograph of high temperature SiC Schottky diode and metal thin film resistive sensors in a ceramic package.

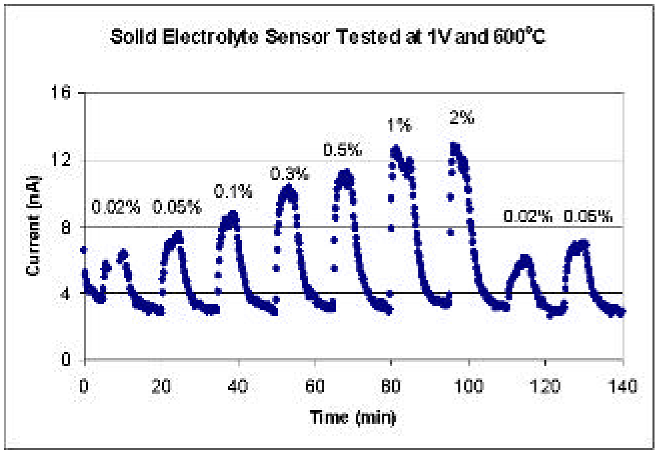

Figure 6: Response of a NASICON based CO_2 sensor tested at 1 volt, 600 °C to varying CO_2 concentration: .0.02%, 0.05%, 0.1%, 0.3%, 0.5%, 1%, and 2%.

Sienna Technologies Inc.: Sienna Technologies Inc., is working with NASA GRC to develop and commercialize SiC power Schottky diode and pressure sensor packaging technologies. Packaged SiC MEMS piezoresistive pressure sensor with a stainless steel package has been successfully tested for short term operation at temperatures up to 600°C. The testing results of packaged sensors at high temperatures show excellent linear response with respect to pressure at constant temperature. The company is working with NASA GRC to dramatically improve thermal reliability of SiC pressure sensor at high temperatures. Both, SiC sensors and packaging systems need long term high temperature validation before commercialization. Products are expected to be commercially available within the next a few years. Figure 7 shows a SiC high temperature pressure sensor. Sienna Technologies Inc., is a major commercial manufacturers of polycrystalline AlN substrates and other AlN products.

Figure 7: SiC high temperature pressure sensor developed by Sienna Technologies and NASA Glenn Research Center.

Kulite Semiconductor Products: SiC dual-resonant-beam MEMS pressure sensors developed by Kulite Semiconductor Products have been demonstrated functional at temperatures up to 600°C (Kurtz *et al*, 2004). Packaged piezoresistive pressure sensors (developed with NASA GRC support) have been tested at 500°C on an aerospace engine. Kulite Semiconductor Products is also developing Si (SOI) MEMS pressure sensors for operation at elevated temperatures. Long-term testing and validation of these products, especially the packaging system, are still needed to further improve quality and thermal stability/durability of the products.

Figure 8: High temperature SiC piezoresistive pressure sensor packaged with stainless steel package by Kulite.

Glennan Microsystems Inc. (GMInc.): The stated vision of GMInc. is to accomplish the challenging task of commercializing microsystems for harsh environments such as high temperature. To achieve this vision, GMInc., relies on a strategic alliance of industry, academia, and government. GMInc., has a team of its members to identify market opportunities, direct technology investments, and leverage resources to create pre-competitive technology that can sense, communicate, and control in high temperature and chemically challenging environments. The interest of GMInc., is to build and commercialize microdevices with compatible packaging technologies that can operate routinely and cost effectively at high temperatures for long periods of time and has built upon the efforts of the Glennan Microsystems Initiative.

IJ Research: IJ Research has been working under US Army and Navy contracts on packaging technology for high power, high temperature (up to 500^{o}C) devices, such as a high power laser diode arrays. AlN chip level packages for electronics passed extreme condition tests including thermal shock, thermal cycle, a lifetime test at 500^{o}C, and room temperature hermetic tests before and after these thermal excursions. Currently, chip level packages are commercially available for high temperature high power devices packaging. A die-attach material and process compatible to both package and device chip is needed to use this technology. Long term reliability tests of these packages with power devices are needed to further validate packaged devices and packaging performance.

Honeywell: Honeywell has SOI devices/circuits on the market for applications at temperatures up to 300^{o}C. These products include: linear amplifier in 4-lead pin-out ceramic Dual-In-Line-Package (DIP), analog switch in 4-lead standard pin-out ceramic DIP, 12-Bit analog-to-digital (A/D) converter, 80C51 microprocessor, and a pressure sensor/transducer. Most of these products have been tested for 225 – 300^{o}C long term (5 years lifetime) operation. According to customer testing, some of these products can operate for short-term at 350^{o}C.

Endevco Corporation (Stockholm, Switzerland): Endevco has commercially available high temperature dynamic pressure sensors with packaging for measurement of pressure up to 500 psi at temperatures up to 320^{o}C.

Research Activities at Universities:

Case Western Reserve University: Case Western Reserve University (CWRU) works with NASA GRC on multiple tasks of high temperature chemical sensors, electronics, and related packaging and has design, fabrication, and testing facilities and capabilities in these areas. The micro-fabrication lab in CWRU has unique expertise in growth of polycrystalline SiC material for high temperature MEMS research. CWRU was also one of the key university partners of Glennan Microsystems Initiative (GMI) with focus on SiC harsh environment microsystems. The Micro-fabrication Center and Electronics Design Center at CWRU currently have significant efforts working with NASA GRC in high temperature SiC microsystems and packaging under various NASA programs including NEPP. CWRU has rich experience in thick-film materials, fabrication, and applications, and has collaborated with NASA GRC for many years in high temperature gas sensor research. These gas sensors include hydrogen, hydrocarbon, NO_X, CO, and CO_2. The Department Electrical Engineering and Computer Science collaborates with NASA GRC on high temperature SiC device/circuits design and testing. Under the NEPP program, CWRU assists NASA GRC in the design, fabrication and testing parts of thick-film packaging materials and components for high temperature reliability testing.

Auburn University: Auburn University is investigating the packaging of SiC devices for high temperature applications (Johnson, 2004). Specific activities include substrates, metallizations, brazing materials (including SiC contact pad stacks) and processes for SiC die attach, wire bonding, and high voltage passivations. The substrate effort is focused on Si_3N_4 ceramic substrates with brazed copper foil for high current carrying capability. A particular research effort is to identify protective finishes to use on Cu for temperatures of 350^{o}C and higher when exposed to air. Inter-diffusion between metal layers is a significant issue.

Two braze systems are being investigated, Au-rich Au-Sn and Au-Ag-Si. Both systems offer the advantage of lower temperature brazing while achieving higher temperature capability through diffusion (which raises the melting point). Figure 9 shows die shear (3.8mm x 3.8mm die) results after storage at 350°C with the Au-Sn braze. Au-In was used as a baseline.

Large diameter (250µm) Au and Pt wire bonding is being studied for top side electrical connection. Au wire provides higher electrical conductivity, while Pt wire has better high temperature mechanical properties. The challenge with large diameter wire is the local stress at the bond pad site due to the coefficient of thermal expansion mismatch between the wire and the SiC die.

High temperature passivations are needed for high voltage SiC devices. Polyimide is showing promising results at 300°C, but alternate materials are being investigated for use above 300°C.

While the efforts are currently directed to SiC power devices, Auburn has also studied the packaging of small signal SiC devices and the high temperature characteristics of resistors.

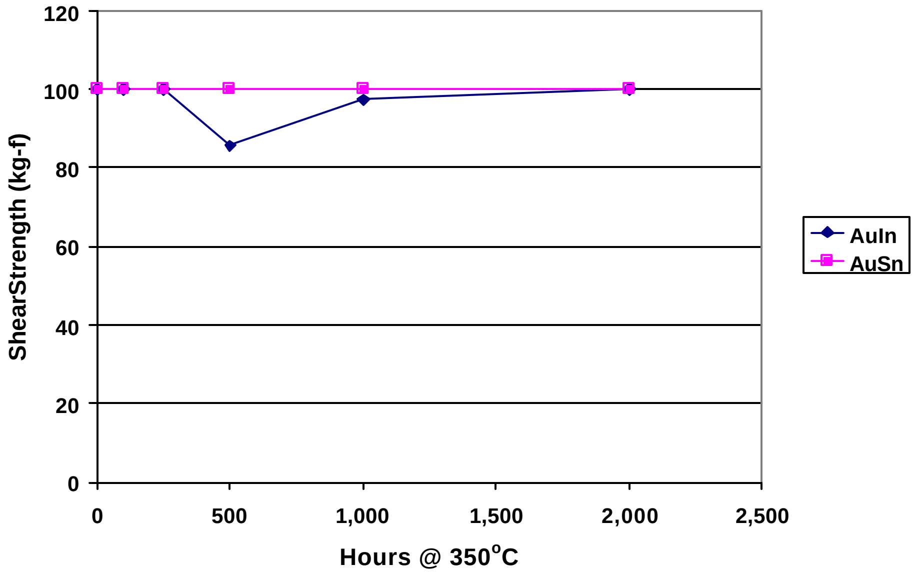

Figure 9: Die shear of 3.8mm x 3.8 mm die after storage at 350°C with the AuSn braze, AuIn was used as a base line (measured by Prof. Johnson's group at Auburn University).

University of Maryland: University of Maryland is presently creating models to assess the reliability of packaging components and materials for SiC MEMS sensors and associated electronics by interconnect fatigue related to both die-attach and wirebonds (Meyyappan and McCluskey, 2003). This modeling is based on an understanding of the fundamental thermo-mechanical and electrical degradation mechanisms. University of Maryland is also conducting measurements of mechanical properties of Au thick-film materials at elevated temperatures. The University of Maryland research team has rich experience in plastic encapsulated microcircuits in the temperature range of 150°C to 200°C, and modeling of packaging for SiC MEMS sensors using finite element analysis (FEA) for operation at temperatures at 500°C. The team at University of Maryland also possesses expertise in the areas of thermo-mechanical and mechanical fatigue modeling, application of the physics-of-failure method for assessing and enhancing reliability, determining material constitutive properties at elevated temperatures, and characterizing materials compatibility and degradation for high temperature electronics. The Computer Aided Life Cycle Engineering (CALCE) Electronic Products and Systems Center (EPSC) at the University of Maryland is one of the originators of the physics-of-failure approach to reliability assessment. Facilities include a range of environmental testing equipment including temperature, temperature cycling, thermal shock, temperature-humidity, altitude, high g force, shock, vibration, and industrial gas exposure testing equipment, some of which can be used to examine devices at high temperatures.

3. Producibility/manufacturability and Commercial Vendors

The Glennan Microsystems Inc., a company developed from a previously NASA supported harsh environment microsystem technology initiative is planning to commercialize various high temperature and harsh environment sensors/actuators with packaging technology in the next few years. Kulite Semiconductor Products has commercialized SiC high temperature pressure sensors for short term applications. High temperature chip level packages for high temperature, high power electronic devices are available from IJ Research. The products of Sienna, Kulite, and IJ Research products have been evaluated/validated for short term applications so far partially because more packaging work is needed. Currently, the high temperature, low power 8-pin packages of AlN and 96% alumina designed at NASA GRC are fabricated by a commercial vendor. The packaging technology that NASA GRC is evaluating is not limited to applications for NASA missions; it is also suitable for commercialization and large scale production of other (non-SiC) high temperature operable devices/sensors. Besides these SiC sensors/devices and packaging technologies designed for temperatures up to 500-600^{o}C, Honeywell has SOI products (both die and multi-chip packaging module) for applications in a temperature range from -55 C to +300^{o}C as indicated in section 2. Complete packaging manufacturers for 300^{o}C operable systems include Honeywell and CTS Corp. *et al*.

The manufacturers for advanced packaging materials evaluated for high temperature applications include precious metal thick-film manufactures: DuPont, Electro Science Laboratories Inc., Heraeus, Ferro Microelectronics *et al*. AlN ceramic substrate manufactures include Carborundum (Saint-Gobain Advanced Ceramics), Hitachi, Coors Ceramics, Kyma, Sienna Technologies.

4. Applications

An advanced electronic sensing system is crucial to integrated vehicle health monitoring. This is evidenced again by the recent Columbia tragedy: the earliest warning signal of vehicle failure was the unusual behaviors of the temperature/pressure signals near the left wing. This illustrates both importance of systems that operate in extreme environments, and the potential capability of a distributed electronic sensing system on an advanced spacecraft. More durable sensors and electronics would have at least provided investigation with valuable clues regarding the cause of the tragedy.

NASA is developing next generation aerospace engines with self-monitoring and self-control capabilities. In order to achieve this technology, a microsystem which is able to operate *in situ* within a high temperature combustion environment is essential to real time monitoring and control of engine operation and combustion processes. The Propulsion Instrumentation Working Group (PIWG) concluded that high temperature operable sensors for real time and *in situ* combustion characterization are needed for the next generation aerospace engines. These microsystems based on high temperature MEMS sensors and electronics not only improve the capability of the next generation engines but also improve the overall reliability of the engine system. High temperature operable electronic systems can reduce electrical wires/connectors and the gas/liquid cooling system. These extended wiring and mechanical systems are certainly an overburden to the vehicle reliability. High temperature microsystem based sensing and control systems not only improve overall health and reliability of the engine system but also improve the environment compatibility of the next generation aeronautic and spacecrafts. For an example, optimization of combustion processes can save fuel and significantly reduce emissions.

Knowledge of inner solar planets is important to better understand our earth and the environment of our earth. The previous Venus explorations indicated that the planet surface and atmosphere temperature is about 500°C and the atmosphere is very corrosive (acid). So any diving or landing probes to Venus must be able to withstand a high temperature and a reactive chemical environment. Many sensors have to be directly exposed to high temperature. A cooling system for an electronic system for any long term operation in 500°C environments is apparently not feasible. Therefore, high temperature microsystems and packaging technologies are necessary for these inner solar planet probes. High temperature gas chemical sensors, pressure sensors, acoustic sensor, and temperature sensors are primary sensors for characterization of Venus atmosphere and surface. An Extreme Environments (sensors and electronics) Technologies for Space Exploration workshop organized by Code Q and S was held in Pasadena in May 2003. **The workshop concluded that 500°C electronics and sensor technologies are essential to future NASA space missions to inner solar planets such as Venus.**

5. Reliability and Radiation Issues

For high temperature Microsystems, the reliability at both device and packaging levels are big concerns. At temperatures up to 600°C long term reliability of materials and joining interfaces between different materials are basic issues. The reliability concern of a complete packaging system is electrical as well as mechanical. As discussed in the previous section, the ceramic substrate and Au thick-film metallization based electrical interconnection system has been successfully evaluated at 500°C with 50 mA DC bias for over 5000 hrs. However, we observed that the thin pure Au wires degraded, as evidenced by very slow increase of wire resistance. For long-term operation in extremely dynamic thermal environments (at temperature rates above military standard of thermal shock rate) this kind of degradation will become more apparent and will need to be addressed.

Both operation and performance of MEMS sensors and electronics can be sensitive to the thermal mechanical stress generated in the die-attach assembly due to the mismatch of thermal expansion (CTE) between the die material (such as SiC), the substrate material, and the die-attaching material. For high temperature microsystems, including MEMS devices, the thermal reliability is even more critical. First, the environment temperature range is much wider compared with that of conventional electronics, and second the MEMS operation is at least partially mechanical so both the device configuration and device response can be very sensitive to thermal stresses on the device/chip. Therefore, the thermal stress of the die-attach structure must be suppressed in order to achieve long term precise and reliable operation because thermally induced stress may generate unwanted device response to the thermal environment.

As indicated in Section 2, the basic packaging subcomponents such as ceramic substrates, Au thick-film metallization, Au wirebonds, and conductive die-attach all have been evaluated at high temperature (500^{o}C) in lab. In order to use these subcomponent technologies in an *in situ* application environment, such as fan area of an aeronautic engine, a practical and versatile high temperature packaging module with integration of these subcomponents still needs to be validated with SiC sensors and electronics. This testing module can be a spark-plug type package which is suitable for various SiC sensors with electronics for real applications in various high temperature harsh environments.

6. Qualification Standards and Possibilities

High temperature and harsh environment microsystems and packaging are newly emerging technologies. The Qualification Standards of high temperature microsystems and packaging technology has to be addressed with respect to specific application and operation environments which can be dramatically different from one case to another. For example, for a space mission to Venus (Decadal Survey, Code Q, and Code S) planned recently by JPL, the planet surface gas environment is 460^{o}C and chemically corrosive (high concentration of carbon dioxide). The pressure is 0 – 1305 psi. The probe lifetime requirement is from 3 hrs to one week. For the application of characterization of combustion of an aeronautic engine the environment temperature is 500°C (fan area), the line pressure is up to 500 psi (the burst pressure can be as high as 3000 psi). The minimum lifetime is several hrs for an engine ground test run. However, for a sensor used for self-monitoring/control of a flight engine the lifetime requirement should be 12 months. The chemicals involved in combustion include hydrocarbons, oxygen, carbon monoxide/dioxide, nitrogen oxide, and water vapor. Based on these discussions, qualification standards of high temperature sensor/electronics are very much mission/application dependent. Therefore, mission/application dependent operational and environmental requirements will be used to establish Qualification Standards for high temperature sensors/electronics designated for each NASA mission/application.

7. Products and Technology Readiness Level

Because of the dramatic differences in device/system performance requirements for various high temperature applications, the readiness level of different microsystem/ sensors/devices are different at this stage. The following list indicates the time lines of various high temperature and harsh environment microsystem projects at GRC and other institutions. The list was based on previously planned activities, and may have changed given changes on-going at NASA, and is meant to illustrate the planned development of the technology. In FY04, the development and validation of packaging technology, as a part of the device/system, was planned to meet these time lines to deliver the final products:

a) Sienna Technology Inc., is commercializing SiC high temperature pressure sensors with NASA GRC in the next couple of years.
b) Honeywell has SOI high temperature (up to 300°C) sensors/electronics and packaging modules on market for long-term operation.
c) Kulite Semiconductor Products currently has prototype high temperature SiC and commercialized SOI pressure sensors on market. SOI product has been tested for operation at temperatures up to 538°C. Testing/evaluation of thermal stability and reliability of these products for long term application is expected.
d) GMInc.: Chemical sensors and MEMS sensors tests in engine environment in FY06-09.
e) NASA High Operation Temperature Propulsion Components (HOTPC): High temperature SiC pressure sensor for engine combustion monitoring and control is due in FY05-06.
f) Smart Engine Components task: Acoustic sensor for measurement of temperature distribution of combustion chamber will be tested in a burner in FY06-07.
g) Vehicle System: A high temperature RF telemetry system for wireless data transfer is going to be demonstrated in FY05-06.

With these discussions, the Technology Readiness Level (TRL) of the packaging technology for high temperature sensors and electronics really depends on device and application requirement.

8. Technology Evolution in Near Term

The development of SiC microsystem and packaging technologies is very likely to be in parallel with product validation and commercialization for the next generation (or more advanced) of products. High temperature and harsh environment microsystems and packaging technologies are still very young, so both device and packaging technologies will certainly be in constant evolution in order to meet further requirements for new applications. As we learned from MEMS packaging, it is very unlikely that one package design will fit many high temperature microsystems which include MEMS devices. So we do expect gradual evolution of packaging technology for high temperature microsystems in both near term and long term, however, at this stage we do not see abrupt technology change in the near term. However, many challenges of high temperature devices packaging are at material level so emergence of new materials, such as nano materials, having superior properties meeting packaging needs may bring significant momentum to high temperature device packaging.

9. Specification and/or Requirements for Technology Items

The basic specifications of a packaged high temperature harsh environment microsystem include maximum operational temperature, lifetime, maximum temperature rate/cycle lifetime, maximum power dissipation, thermal drift *etc*. Specifications of high temperature harsh environment microsystems and packaging systems should be systematically established. However, it has been noticed that very few of current commercialized products for operation at temperature at 500^{o}C and above are provided with all these specifications. This reflects that the high temperature electronics and sensor technologies are still at early stage. Therefore, NASA needs its own validation capability for high temperature device and packaging for aerospace applications. Establishing a qualification/specification system for high temperature harsh environment microsystems is vital to the success of application of this technology down the road.

10. Considerations Addressed in All Three NEPP Projects

The reliability considerations of a complete product should be covered by all three aspects of packaging, parts, and radiation. Various high temperature harsh environment microsystems needed for NASA missions should also be validated/evaluated as individual parts as these parts approach application. SiC has a wide energy bandgap so this material has very good resistance to radiation, and therefore, SiC microsystems are very suitable for space applications. This indicates that radiation related reliability should also be considered later for SiC products. However, as it was discussed before, a high temperature packaging technology is essential for testing high temperature devices. Gold thin-film coated tungsten 'high temperature' probe tips fail at 450^{o}C, so electronic devices can not be long-term tested at the wafer level using conventional probe stations. Therefore, high temperature testing of microsystems is not feasible without an appropriate package. This indicates the critical role and the importance of high temperature long-term operable packaging technology to infuse SiC high temperature harsh environment microsystem technology into NASA missions.

11. Conclusion

High temperature microsystem packaging technology is essential to long term evaluation, application, and commercialization of high temperature microsystems technology which is vital to NASA inner solar space missions and aeronautic engine technology, and many commercial applications. Therefore, high temperature device packaging has been an active field for both technology research and products development in federal research laboratories, private industries, and academic laboratories. At current stage, validated high temperature packaging technologies suitable for long term operation at temperatures up to 500^{o}C is a critical element to expedite application and commercialization of high temperature SiC microsystems. NASA GRC has validated basic packaging subcomponents for long-term high temperature applications. Private industries have started to commercialize various high temperature sensors. At this stage, systematic validation of practical packaging systems which can accommodate various high temperature sensors and electronics would be important and critical to both products development and commerciallization. A long term validated high temperature packaging technology, as an essential part of high temperature microdevices technology, will benefit both NASA's space missions and commercial technologies.

Acknowledgements

The author of this report wants to thank Drs. Lawrence G. Matus and Gary W. Hunter for their proofreading of this report. The author also thanks Prof. Patrick McCluskey at University of Maryland, Prof. C.C. Liu at Case Western Reserve University, Prof. Wayne Johnson at Auburn University, Dr. Ender Savrun and Vu Nguyen at Sienna Technologies, and Dr. Alex Ned and Haydee Otero at Kulite Semiconductor Products for their inputs. Author thanks Dr. Philip G. Neudeck, Glenn M. Beheim, and Robert S. Okojie for their contributions. This survey report is supported by Wide Band Gap Electronics task of NASA Electronic Parts and Packaging program in FY2004.

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., *Deep Reactive Ion Etching for Bulk Micromachining of Silicon Carbide*, The MEMS Handbook, CRC Press, Boca Raton, LA, 2002.

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

Chen, L.-Y. and Lei, J.-F., Packaging of Harsh-Environment MEMS Devices, the MEMS Handbook, CRC Press, Boca Raton, August 2002.

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*, Proceedings IEEE Sensors 2002, Orlando, FL, June 12-14, 2002.

Hunter, G.W., Liu, C.C., and Makel, D.B. (2001), *Microfabricated Chemical Sensors for Aerospace Applications*, Chapter 22, the CRC MEMS Handbook, CRC Press, Boca Roton, LA, 2002.

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*, the Proceedings MRS Spring Meeting, San Francisco, CA, April 12-16, 2004.

Johnson, R.W., Palmer, M., Wang, C., Liu, Y. (2004), Packaging Materials and Approaches for High Temperature SiX Power Devices, Advanced Microelectronics, Vol. 31, No.1, January/February 2004.

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

Mryyappan, K., McCluskey, P., and Chen, L.-Y. (2003), *Thermomechanical Analysis of Gold-Based SiC Die-attach Assembly*, IEEE Transactions on Device and Materials Reliability, Vol. 3, 4, December, 2003.

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

Okojie, R.S., Spry, D., Krotine, J., Salupo, C., and Wheeler, D.R. (2000), *Stable Ti/TaSi2/Pt Ohmic Contacts on N-Type 6H-SiC Epilayer at 600C in Air*, Matrials Research Society Symposia Proceedings, MRS, Warrandale, PA. Vol. 622, pp H7.5.1-H7.5.6, 2000.

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

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

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

Xu, J.C. and Hunter, G.W., Liu, C.C., Hammond, J.W., Ward, B., Lukco, D., Artale, M., Lampard, P., and Androjna, D. (2004) , *Miniaturized Thin Film Carbon Dioxide Sensors*, Presentation on 2004 Ceramics Society Meeting, May 2004.