Abstract—The recent increase in transportation costs and the push for cleaner emissions demands advancements in aerospace technology. The current instrumentation used in aerospace applications is costly, and indirect measurement approaches are often employed due to the inability to locate sensors in harsh environments. Health monitoring technologies for the development of a distributed sensor network can be utilized to improve engine efficiencies and reduce emissions while maintaining safety. This paper reviews the recent advancements in silicon carbide (SiC) process technologies and demonstrations of SiC sensors and electronic circuits in hostile environments, which supports the use of SiC technology for health and performance monitoring of aerospace systems. Further development of this technology can ultimately improve the performance, reliability, and emissions of aerospace systems. However, challenges still remain for the realization of a distributed sensor network for harsh environment applications such as aerospace.

Index Terms—Aerospace, harsh environment, high-temperature sensors, silicon carbide (SiC), structural monitoring.

I. INTRODUCTION

Aerospace, recognized as one of the top-five high-technology industries in the world [1], faces new challenges in order to sustain its growth and achieve progressive benchmarks in the exploration of space and beyond. High industrial growth in various regions of the world has increased the volume of aerial transportation, leading to an increased dependence on fossil fuel and production of greenhouse gas emissions. In addition, higher transportation costs and increased maintenance cycles are affecting this industry’s growth. New technologies that enable more efficient jet engines and lightweight structural designs can improve the growth of aerospace industry by increasing fuel efficiency, reducing emissions, and decreasing maintenance cycles. One such technology that has gained interest recently is the real-time health monitoring of various aerospace systems with a distributed sensor network (Fig. 1).

As a result, many groups are investigating sensor technology for aerospace applications. For example, the behavior of embedded sensors in composite materials for detection of localized stresses and crack propagation is being studied for real-time failure prediction and monitoring [2]–[4]. In addition, harsh environment sensors for the real-time monitoring of combustion processes are being developed [5], [6]. These technologies require sensors that can operate beyond the capability of traditional Si-based sensors. More specifically, sensors must have the ability to operate in environments such as the combustion chamber of jet engines and upon exposure to extreme temperature excursions of space. In addition, sensors must be able to withstand the high-temperature, high-pressure prepreg forming processes used to fabricate composite matrices.

A semiconductor material that has gained much attention for harsh environment sensing applications is silicon carbide (SiC). This is due to its attractive electrical and mechanical properties as well as chemical stability [7]–[10]. The high sublimation temperature of SiC (2830 °C) is an example of the stability of this material at extremely high temperatures. This is due to the strong covalent bond between the Si and C atoms. In addition, the wideband gap of SiC (3.0 eV) limits the generation of intrinsic carriers in high-radiation and high-temperature (as high as 1000 °C) environments. The resulting electrical stability of SiC enables high-temperature operation of sensors and electronic circuits and can ultimately eliminate the need for active cooling systems. In addition, the design of high-bandwidth sensors can be obtained through the use of materials with high acoustic velocities. The acoustic velocity of SiC is 11.9 × 10^3 m/s and is higher in comparison to those of Si (9.1 × 10^3 m/s) and gallium arsenide (3.8 × 10^3 m/s). Another
material that is being developed for high bandwidth devices is diamond with an acoustic velocity of $17.2 \times 10^3$ m/s; however, SiC has superior chemical inertness in comparison. More specifically, SiC remains stable in high-temperature, oxidizing environments, whereas diamond graphitizes [11]. It is clear that the development of SiC into a mainstay platform material for harsh environment sensor applications can greatly benefit aerospace applications.

This paper will present a review of the current status of aerospace instrumentation and monitoring approaches for the assessment of components such as landing gear, aircraft body structures (fuselage and wings), and jet engines. In addition, recent demonstrations of operating SiC sensors and circuits in high-temperature, high-shock, high-pressure, and corrosive environments will be reviewed. These compelling demonstrations in hostile environments support the use of SiC sensors for the monitoring of aerospace systems. However, challenges still remain in realizing a distributed sensor network; several of these challenges will be discussed in this paper. It should be noted that although aircraft components are the focus of this review, the concepts can be readily extended to spacecraft systems.

II. NEEDS IN AEROSPACE SYSTEMS MONITORING

A. Landing Gear

Landing gear failure has been the most dominant cause of emergency declaration by pilots in the past decade. The urgent need for safe and reliable landing has turned this system into a critical component for aircrafts, space shuttles, helicopters, and unmanned planes. The landing gear system [Fig. 2(a)] is recognized as one of the main contributors to total aircraft noise [12]. The major failure mechanism of landing gear is the fracture of the outer cylinder attachment lug, manufactured from an aluminum alloy, due to abrupt rupture of the connections caused by fatigue and cracks [Fig. 2(b)] [13]. In addition, deviations from the tire inflation pressure set point can lead to explosion of the tires, which may end catastrophically. To avoid such failures, it is beneficial to obtain accurate knowledge and real-time assessment of the forces in the structural members and tire pressures. Currently, landing gear systems are heavily tested in laboratories before installation, utilizing a sensor instrumented monitoring system (wired or wireless) to log the velocities, pressures, and impacts experienced during operation. The collected data is then analyzed by software to assess the structural health under various conditions. Although this measurement approach is low in cost and software has been enhanced for improved accuracy, the indirect diagnosis is prone to feed-through noise caused by the connection leads. These types of computational errors could be catastrophic in the field. Therefore, direct and real-time measurements of forces and pressures at various locations in the landing gear system can significantly improve the safety of current approaches. However, the development of bonding techniques for adhering packaged sensor modules to metal landing gear systems with sufficient strain transfer must be developed.

B. Fuselage and Structural Components

The recent increase in aviation costs has led to a push for more efficient aircraft structural designs while maintaining safety. In addition, a large number of operational aircrafts have exceeded their design lifetime, which asserts the need for precise health monitoring to improve the safety of aerospace fleets [14]. In recent years, composites have been used in the design of aircraft structural components such as the fuselage, wing skins, and tail skins due to their lightweight and high-strength properties. Higher engine efficiencies can be obtained by improving the properties of composite materials and as a result, research in developing new composite materials technology is being investigated by many groups [3], [15]. For assembly of large composite structures, aluminum fasteners and beams are utilized leading to large coefficient of thermal expansion (CTE) mismatch during operation due to large temperature excursions (as high as 130 °C) [16] and corrosion of hidden metal components in humid conditions [17]. In order to avoid such failures, damage
techniques to measure strain, temperature, and pressure with a digital telemetry [22]. The development of robust sensor technology that enables in-chamber measurements of turbine combustion pressures, and temperatures and mechanical strain can greatly improve upon today’s jet engine technology.

III. STATUS OF SiC SENSOR DEVELOPMENT

A. SiC Process Technology

Over the last decade, there have been major advancements in SiC processing technology for the development of harsh environment sensors and electronics. For example, low-defect density, 100 mm diameter, SiC substrates are now available from several commercial suppliers [23], [24]. These vendors also have the capability of growing epitaxial SiC films with low-resistivity and good-crystalline quality for the production of SiC electronics [25]. Various research groups have demonstrated the growth of low-stress, low-resistivity, polycrystalline SiC thin films with CVD and in situ doping [26], [27]. These films are suitable for the fabrication of microscale structures, such as cantilevers or comb drives [28], [29]. In addition to SiC thin films, SiC nanostructures are also being synthesized for new electronic materials [30]. Industry along with various research groups have developed relatively high-rate etch recipes (up to 2 μm/min) and dedicated SiC plasma etch tools are becoming more available [31]. More importantly, these advancements in processing technologies have lead to the realization of SiC sensors (pressure, strain, and temperature) as well as electronic circuits.

B. SiC Pressure Sensors

Readily available pressure sensors based on Si microfabrication technology are typically employed for the measurement of pressure in gas turbines. However, as mentioned previously, costly cooling systems are often used to prevent failure of the sensors [32]. In addition, Si pressure sensors cannot survive corrosive and oxidizing environments of jet engines and must be located far (<1 m) from the hot gas streams during diagnostic measurements [22]. These challenges in pressure detection can be overcome through the development of more robust sensor technology.

Doped SiC has demonstrated stable piezoresistive behavior at elevated temperatures (up to 800 °C) [33]. As a result, many industrial and academic groups have investigated the use of piezoresistive SiC in the design of pressure sensors for high-temperature operation. The selective growth of 3C–SiC onto Si surfaces of silicon-on-insulator (SOI) wafers has been used as pressure sensor technology, and operation up to 200 °C was observed [34]. In an effort to increase the operating temperature beyond 200 °C, SiC diaphragms have been employed in pressure sensor designs. The use of SiC diaphragms improves the CTE mismatch between the piezoresistive elements and the diaphragm, leading to a design that can operate under large temperature swings. An approach to that uses a photo-electrochemically etched crystalline 6H–SiC diaphragm, and epitaxially grown N-type 6H–SiC piezoelectric elements has been used to create an all-SiC pressure sensor [35]. This sensor design has the ability to detect pressures as high as 6.9 MPa at...
Fig. 4. SEM of the diaphragm surface of a capacitive SiC pressure sensor that has been operated in pressures up to 4.8 MPa and temperatures up to 574 °C [41]. 600 °C with insignificant junction leakage and no plastic deformation [36]. As an alternative to piezoresistive technology, absolute pressure sensors with capacitive transduction schemes have been designed with thin film diaphragms [37], and such devices have operated at temperatures up to 574 °C and pressures of 4.8 MPa (Fig. 4) [38]. For moderate-temperature operation of pressure sensors in harsh chemical environments, SiC coatings have been used as anti-erosion protection layers for Si pressure sensors and resistance to KOH etching was observed.

C. SiC Strain Sensors

A variety of physical conditions, such as temperature swings, fluctuating pressures, large external forces, and moments, can induce internal stresses and strains, which may lead to fatigue, delamination, brittle failure, plastic, and permanent deformations in aerospace components. Strain sensors enable the ability to measure internal forces and stresses through constitutive models of the active material. For accurate measurement signals, strain sensors must be attached to the active structure for displacement transfer. Such placement can impose harsh and aggressive environmental constraints, which can alter sensor resolution and accuracy. Large vibrations, high shocks, presence of corrosive gases, continual contact wearing, and high temperature are among these constraints. Commercial strain sensors have not been able to fulfill the increasing demand for embedded sensors to accurately monitor various measurands in physical systems such as aerospace components.

As previously mentioned, the superior mechanical and chemical properties of SiC have motivated the use of this material as chemical resistant coatings and the structural material of harsh environment sensors. Resonant sensing approaches, based on shifts in the natural resonant frequency caused by induced stresses in sensing elements, enables high-bandwidth and resolution strain measurements [39]. The recent development of an SiC resonant strain sensor [5] provides a new solution for demanding applications such as aerospace. This sensor exhibits a strain resolution of 0.11 με in a bandwidth from 10 to 20 kHz in air, has survived shocks of 10000 g, and operated in elevated temperatures up to 300 °C and in corrosive ambients (Fig. 5). In addition, a similar strain sensor design using Si as structural material with a nanometer-thin layer of low-pressure CVD (LPCVD) polycrystalline 3C-SiC as passivation demonstrated protection against oxidation and corrosion while maintaining the high bandwidth and resolution of the uncoated Si resonant strain sensor [40]. In addition to resonant strain sensors, low-frequency capacitive strain sensors have also been developed utilizing SiC as a platform material. One advantage of capacitive sensing is the ability to obtain relatively temperature insensitive designs. In recent efforts, a high-resolution SiC coated capacitive strain gauge (Fig. 6) was developed and demonstrated a strain resolution of 0.88 με in a 120-Hz bandwidth [41], [42]. This sensor demonstrated operation at temperatures up to 370 °C in dry steam ambient. This design utilized a gap-closing sense element to detect capacitance changes that correlated to the applied strain. In addition, the
SOI-based Si sensor was passivated with a conformal coating of LPCVD polycrystalline 3C–SiC (60 nm thick) for chemical resistance. It should also be noted that this sensor utilizes commercially available SOI substrates, which is low-cost and manufacturable platform and is attractive for aerospace applications such as landing gear and structural components.

D. SiC Temperature Sensors

Temperature measurements can aid in the monitoring of jet engine components, leading to higher fuel efficiency and improved safety. In addition, temperature sensors can be colocated with mechanical sensors for temperature compensation. Due to the availability of low-cost thermocouples that utilize junctions and ceramic packaging, minimal research has been focused on the development of SiC temperature sensors. However, the compatibility and integration of SiC temperature sensors with SiC sensors could lead to single chip solutions. Consequently, thin film SiC elements have been utilized as a thermometer to measure the temperature change as a function of resistance [43]. More recently, SiC JFETs have been characterized at various temperatures to be used as temperature monitoring circuits [44]. This approach is advantageous, as it can be readily integrated into the fabrication of SiC circuits.

E. SiC Electronic Circuits

The interfacing of electronic components such as data acquisition and telemetry circuits with sensors is necessary for control and monitoring schemes. The development of this technology also aids in the realization of a networked sensor system. CMOS technology utilizing Si is limited to temperatures below 300 °C due to an increase in thermal carriers in junction devices and leakage currents [45]. As a result, the development of SiC electronics that are compatible with the operation environments of SiC sensors is being pursued by industrial and academic groups. The epitaxial growth of SiC on crystalline substrates and ion implantation has enabled junction-based devices to be fabricated [46]. For example, 6H–SiC n-channel JFET structures have been developed and used to create logic gates operated at 600 °C [47]. In addition, the characterization of SiC JFET components has lead to the design of differential amplifiers for signal processing and demonstrated operation at 450 °C [48]. More recently, SiC MESFET technology has been commercialized for high power electronic and wireless applications [49]. These components have been utilized to create simple telemetry circuits (Fig. 7) for SiC pressure sensors and have operated at 400 °C with telemetry distances of 1 m [50]. It is clear that the roadmap for SiC electronics is to push circuit operation to even higher temperatures. However, challenges still remain such as reduction in power consumption and the use of stable metallization and dielectric materials.

IV. REMAINING CHALLENGES

Although there have been recent advancements and compelling demonstrations in SiC technologies, the realization of a distributed sensor network system for aerospace applications requires further development. For example, additional sensing methods such as acoustic vibration sensors complements strain sensors for the monitoring of structural components and should be developed in an SiC platform. In addition, robust packaging methods must be further developed for integration, protection, and long-term operation of sensor components. More specifically, encapsulation, bonding, and interconnects should be further developed. In addition, high-temperature operation met- allization and dielectric materials that are compatible with SiC processing steps and aerospace operation environments should be developed to prevent unintentional diffusion and alloying of materials that can degrade the performance of devices. This will enable the advancement of electronic circuit technology to create chip-scale components such as data acquisition circuits and transceivers. Also, low-power sensing platforms should also be investigated. More specifically, passive platforms with RF backscattering and the development of energy scavenging units will also advance this technology.

V. CONCLUSION

The aerospace industry can benefit from new technology to address the increase in transportation costs and the need for cleaner emissions. A vision of a distributed sensor network for real-time health monitoring of various aerospace systems was presented in this paper for increasing fuel efficiency and reducing emissions by enabling the design of efficient jet engines and structural components while maintaining safety. The current status of SiC sensor technology has been discussed in this paper, and the compelling demonstrations of sensor and circuit operation in harsh environments supports the use of SiC as a platform material to advance current aerospace instrumentation techniques. However, SiC technology is still in the research state, and further developments are required for the realization of an SiC sensor network for aerospace applications.

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