

Smart, In Situ, Wide Range Pressure Sensor for Advanced Engine Controls

Michael Usrey, Kevin Harsh, and Alexander Brand
Sporian Microsystems, Inc.

R. Steve McKown
Titanium Mirror, Inc.

Alireza Behbahani
Air Force Research Lab.

ABSTRACT

Air Force Research Laboratory (AFRL) is pursuing development of advanced, distributed, intelligent, adaptive engine controls and engine health monitoring systems. The goals this pursuit are enhancing engine performance, safety, affordability, operability, and reliability while reducing obsolescence risk. The development of smart, high-bandwidth, high-temperature-operable, wide-range, pressure/temperature multi-sensors, which addresses these goals, is discussed. The resulting sensors and packaging can be manufactured at low cost and operate in corrosive environments, while measuring temperatures up to 2,552 °F (1,400 °C) with simultaneous pressure measurements up to 1,000 psi (68 atm). Such a sensor suite provides unprecedented monitoring of propulsion, energy generation, and industrial systems. The multi-sensor approach reduces control system weight and wiring complexity, design time, and cost, while increasing accuracy and fault tolerance. In situ pressure sensors reduce size and weight while eliminating failures associated with hypo-tube fouling. High-bandwidth sensors support advanced compressor and combustor control schemes that facilitate higher thrust, reduced fuel consumption and reduced emissions. Smart sensors are a key enabling technology for distributed engine control which is an important architectural paradigm shift to achieve increased flexibility, scalability, fault tolerance and performance while reducing weight, lifecycle costs and obsolescence risk. Current efforts include combining the sensor technology with other high-temperature electronics to produce smart sensors for distributed engine controls, capacitive transducer elements with increased dynamic bandwidth, and advanced high-temperature sensor packaging technologies. Test results demonstrating technology readiness level (TRL) 6 are reported herein.

CITATION: Usrey, M., Harsh, K., Brand, A., McKown, R. et al., "Smart, In Situ, Wide Range Pressure Sensor for Advanced Engine Controls," *SAE Int. J. Engines* 7(4):2014, doi:10.4271/2014-01-2167.

INTRODUCTION

Former Defense Secretary Panetta linked energy and the environment to national security [1], and the Air Force is the largest consumer of fuel in the Department of Defense (DoD) [2]. Commercial airlines are also concerned with reducing fuel consumption and costs [3]. The DoD Versatile Affordable Advanced Turbine Engine (VAATE) program is focused on achieving a 10x improvement in the combined areas of engine capability and affordability [4]. To address these challenges, NATO is championing an Intelligent Propulsion System concept [5].

Active combustion control improves specific fuel consumption (SFC) and reduces the emissions of oxides of nitrogen [6]. In situ, dynamic-pressure sensors are necessary for active combustion control, but current dynamic pressure sensors require active cooling to survive in situ compressor discharge (P3) temperatures, but the installation of active cooling systems increases weight and cost [7].

As military and commercial turbine engine users have sought to increase performance and reduce costs, distributed engine control (DEC) has also been identified as an important architectural model to reduce weight, cost of ownership, and obsolescence risk while increasing flexibility, scalability and fault tolerance [8]. Smart sensors are seen as a key building block for DEC [9].

Model-based life prediction and sensor data fusion are critical technologies for advanced engine health monitoring (EHM) systems [5].

The Propulsion Instrumentation Working Group (PIWG) has identified the need for pressure sensors that can operate under conditions up to 750 psi for engine test and design validation purposes [10]. A goal of the National Aeronautics and Space Administration (NASA) Environmentally Responsible Aviation (ERA) program is to increase compressor discharge/combustor inlet pressures to help increase fuel efficiency and reduce harmful emissions. The ERA goal for the 2020 timeframe is 55 atm/808 psi [11]. Sensors with a wide operating range are needed to support these goals.

The following sections discuss/describe the facilitative high temperature sensing element materials, sensor architecture, and harsh environment packaging; and the overarching smart sensor strategy and features.

HIGH-TEMPERATURE SENSOR, MATERIALS, AND PACKAGING

The subject sensor technology is based on the combination of recently developed silicon carbide nitride (SiCN)-based, polymer-derived ceramics (PDCs) utilized in the sensing element and advanced high-temperature (HT) electronics packaging.

PDC SiCN as a Sensor Material

SiCN-based ceramics are a group of amorphous, high-temperature materials, which possess excellent mechanical and electric properties at temperatures up to 1,800 °C [12,13,14,15,16,17,18,19], which allows for the creation of devices with much higher operational temperatures than silicon carbide (SiC) or silicon-on-insulator (SOI)-based technologies. The synthesis process of the polymer-derived SiCN sensors reported here includes the following steps (Figure 1): i) synthesize and dope polymer precursors, ii) shape and crosslink to form infusible polymer components, and iii) convert the polymer green bodies into ceramic components through pyrolysis. The materials thus obtained are predominantly amorphous ceramic alloys consisting of silicon, carbon, and nitrogen. For improvement of material properties, other elements can be incorporated into the ceramics by doping or modifying the polymer precursors.

The resulting SiCN ceramics have features that make them uniquely suitable for the proposed sensor application including excellent high-temperature thermomechanical properties, corrosion resistance, tunable electrical conductivity, and ease of fabrication and packaging.

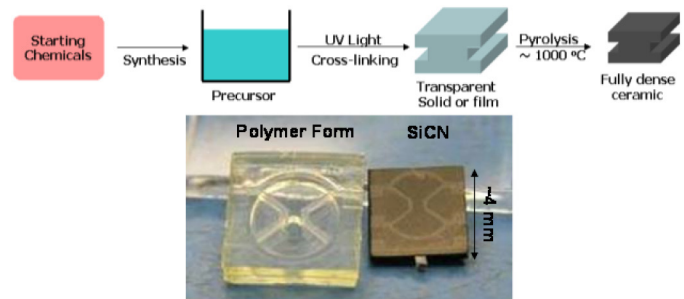


Figure 1. (Top) Basic processing steps for SiCN PCD sensors, (Bottom) photo of a pressure sensor structure pre- and post-pyrolysis.

While synthesized at relatively low temperatures, this new class of materials has shown excellent high-temperature thermomechanical properties. Generally, non-doped SiCN can work safely under 1,400 °C. However, some doped SiCN ceramics are thermally stable and resist large-scale crystallization at temperatures up to 1,800 °C [14]. Due to the absence of grain boundaries, the high strength of SiCN can be retained at high-temperatures. The high-temperature creep resistance exceeds that of polycrystalline SiC and Si₃N₄ [20,21,22]. Compared with other ceramics, the lower density, higher strength, and greater thermal shock resistance make SiCN extremely suitable for surviving dramatic engine transients and temperature excursions. Research indicates that the SiCN materials efficiently self-protect from oxidation [15], and exhibit better corrosion and oxidation resistance than SiC and Si₃N₄ [18,19].

By changing the material composition or doping elements, the electrical conductivity of polymer-derived SiCN can be tailored within a large range, from insulator to conductor. Similarly, using select doping materials the temperature coefficient of conductivity (α) can be varied. Typical values for α used in the reported sensors is 4×10^{-3} at 600 K and 3×10^{-3} at 1000 K, which are in the same range as that of some metals.

The chemical-to-ceramic processing route for SiCN enables the utilization of many well-developed micro-fabrication technologies. Micro-fabrication techniques, such as photolithography, DRIE etching, injection molding, embossing, and precise machining have been employed for the fabrication of SiCN MEMS with customized designs and complex structures [23,24,25,26]. Complex parts can be batch fabricated using traditional manufacturing infrastructure by using polymer materials and processes that are much more cost effective than semiconductor devices.

SiCN Sensor Architecture

The first and most mature versions of a pressure sensor developed by Sporian Microsystems using this material have been based on the piezoresistive effect. Pressure changes manifest as mechanical strain on a thin diaphragm which registers as a change in circuit resistivity. A major problem associated with such piezoresistive pressure sensors is their cross sensitivity to changes in temperature [27]. Thus, a

thermoresistive temperature sensing element is included in the transducer to facilitate accurate temperature compensation of the pressure measurement within the smart sensor. Multi-sensor architectures facilitate redundancy and data fusion. Another, less mature pressure sensor element is under development which is based on a capacitive architecture. High-temperature capacitive pressure sensors are of particular interest due to their low power requirements, lack of turn-on temperature drift, high sensitivity, robust structural nature, dynamic response, and inherent suitability for wireless readout schemes as part of oscillator-based circuits [28]. The capacitive architecture has shown promising results in initial testing [29]. Unless otherwise explicitly stated, results in this paper are based on the piezoresistive sensor architecture.

SiCN Sensor Packaging

Electronics packaging is a group of methods or processes for aggregating electronic components into a system and facilitating their interface to the environment [30]. Conventional electronics packaging includes processes for component attachment, component interconnection, thermal management, system signal conditioning, system protection, system interconnection, and system access [30]. Traditional electronics packaging does not contemplate the elevated temperatures, acceleration loads, and constrained application of an engine environment [31]. Therefore, HT packaging and installation methodology are key to supporting emerging HT sensor and electronics technologies.

Reported packaging for engine applications resembles traditional thermocouple/thermowell probe style hardware. The subject sensor elements are bonded to the end of a ceramic core/rod with embedded electrical feed-throughs. This electrical distribution layer can host both the sensor element at the hottest position (500 to 1,350 °C), and integrated HT electronic components a short distance away at a cooler position (<500 °C) in the probe housing. To support such packaging strategies, the authors have previously developed HT compatible (>1,000 °C) flip chip, ribbon, and wire bonding, along with HT die attach materials processes for integrating both sensor components and HT ICs/passives. In this way, the integration/packaging methodologies closely resemble conventional ceramic multi-chip module (MCM) packaging technologies, but with much higher temperature capabilities. The core is cemented into a HT alloy or ceramic sheath/housing, which includes port fitting for engine mounting and a commercial electrical feed-through gland/seal. The housing is machined to include application-specific features such as screens, threads, flanges, and/or flow channels as appropriate, but no gas or liquid cooling features are needed. Examples of packaged HT sensor elements for turbine engine insertion are shown in [Figure 2](#).

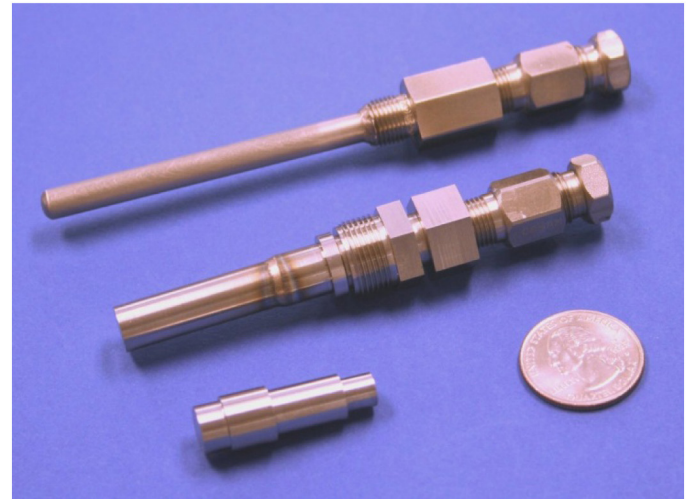


Figure 2. Examples of packaged HT sensor elements for turbine engine insertion

SMART SENSOR STRATEGY AND FUNCTIONALITY

The subject smart sensor strategy and functionalities can be divided into three sections: the electronics, firmware, and digital communications bus.

Electronics

A smart sensor can be thought of as a combination of a sensor, signal conditioning, ADC and digital communications bus interface in one housing or assembly [32]. Other possible smart sensor features include self-test and self-identification [33] along with digital filtering, calibration, temperature compensation and linearity correction [34].

Signal conditioning electronics can include passive and/or active components that act on the analog signals produced by the sensing element. Transformations commonly performed in signal conditioning circuits include isolation, amplification, and filtering [35]. The addition of a microprocessor to the signal conditioning circuit allows smart features to be integrated into traditional analog signal conditioning circuits. For example, assigning an on-board microprocessor to handle calibration greatly reduces the processing required from the data acquisition system, EHM or control system and makes the sensor an LRU. Integrated nonvolatile memory can store the sensor's calibration transfer function, which allows the sensor to output data on a digital bus in engineering units, or as linearized analog outputs. Since the sensor itself is continuously calculating real-time pressure and temperature data, it can monitor the data stream to continuously perform health checks in both firmware and dedicated health monitoring circuitry.