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Sensors and Actuators A 145–146 (2008) 2–8
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

A silicon carbide capacitive pressure sensor for in-cylinder pressure measurement

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Received 9 July 2007; received in revised form 13 September 2007; accepted 18 September 2007
Available online 2 October 2007

Abstract

This paper reports a research prototype of a low-cost, miniature, mass-producible sensor for measurement of high-pressure at operating temperatures of 300–600 °C, e.g., in-cylinder engine pressure monitoring applications. This all-silicon carbide (SiC) capacitive sensor, i.e., a SiC diaphragm on a SiC substrate, takes advantage of the excellent harsh-environment material properties of SiC and is fabricated by surface micromachining. The sensor is packaged in a high-temperature ceramic package and characterized under static pressures of up to ∼5 MPa (700 psi) and temperatures of up to 574 °C in a custom chamber. An instrumentation amplifier integrated circuit is used to convert capacitance into voltage for measurements up to 300 °C; beyond 300 °C, the capacitance is measured directly from an array of identical sensor elements using a LCZ meter. After high-temperature soaking and several tens of temperature/pressure cycles, packaged sensors continue to show stable operation. For monitoring the dynamic cylinder pressure in the combustion chamber, the sensor is packaged in a custom probe and inserted into the cylinder head of a research internal combustion engine. The sensor efficacy is verified against the reference probe used for monitoring pressure in the research engine.

Keywords: Silicon carbide; Poly-SiC; Capacitive; High-temperature; Harsh-environment; Pressure sensor; Engine pressure; In-cylinder pressure

1. Introduction

To enhance fuel efficiency, reduce emissions and improve reliability for future vehicles, it is necessary to optimize the combustion process by using a pressure-based engine management solution. For this type of high-temperature, harsh-environment application, a robust pressure sensor using high-temperature material has to be developed. At the same time, the cost per sensor must be low enough in automotive quantities to allow such technology insertion.

Prototypes of SiC piezoresistive and capacitive pressure sensors have been reported in recent years but only the piezoresistive prototypes are all-SiC [1]. Others have utilized a SiC pressure-sensing diaphragm on a Si substrate [2–4], but the devices suffer from thermal expansion mismatch between the diaphragm and the substrate. Concerns related to the piezoresistive approach include: (i) the relatively small gage factor of SiC at high temperatures; (ii) temperature sensitivity of the piezoresistive readout; (iii) junction leakage current at high temperatures; (iv) the challenge of bulk-etching a SiC substrate to realize the sensing diaphragm. The capacitive approach overcomes these concerns, albeit at the cost of a high-temperature interface electronics requirement, a separate development in our group to realize SiC interface integrated circuits capable of 300–600 °C operation [5].

An all-SiC capacitive implementation overcomes both the piezoresistive concerns, as well as the thermal mismatch issue. In this paper, a surface-micromachined capacitive pressure sensor is presented, which is comprised of a polycrystalline SiC (poly-SiC) diaphragm on a poly-SiC substrate. High-pressure operation of the sensor die in a high-temperature ceramic package is demonstrated up to 574 °C (limited by the testing setup) in a custom chamber. To demonstrate its operation in dynamic pressure environment in an internal combustion engine, the sensor chip is packaged into a custom probe and inserted into a single-cylinder internal combustion test engine.

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doi:10.1016/j.sna.2007.09.015

2. Sensor design

A series of edge-clamped circular sensing diaphragms of different diameter, operating in non-touch (small deflection) and touch modes, were designed for a range of pressure application specifications. The sensor's operational modes were modeled by finite element analysis (FEA) to predict performance. A three-dimensional analysis was performed for enhanced visualization, even though more computationally expensive than a simpler two-dimensional axisymmetric model. The Young's modulus of our heavily doped poly-SiC is ∼330 GPa, previously determined by bulk-micromachined membranes and surface-micromachined resonators fabricated from our [6]. Fig. 1 shows an example three-dimensional model and the predicted performance for a diaphragm operated in small deflection mode up to ∼1.8 MPa (250 psi). The sensor diaphragm has a diameter of 136 μm and a thickness of 3 μm, while the zero-pressure capacitive gap is 1.5 μm. Fig. 2 shows the contact-mode operation of a 194 μm-diameter diaphragm sensor

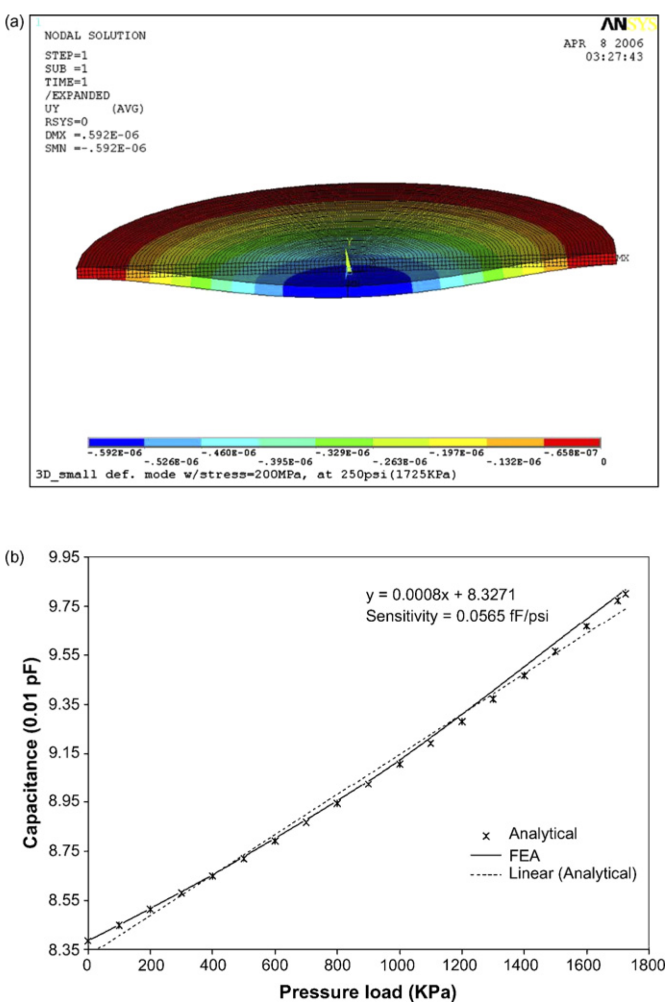

Fig. 1. Sensor modeling results: (a) three-dimensional finite element simulation for small deflection (i.e., non-contact mode) operation up to a pressure load of ∼1.8 MPa (250 psi) and (b) linear fit to the model prediction showing a non-linearity of 0.8% (deflection not to scale in (a)).

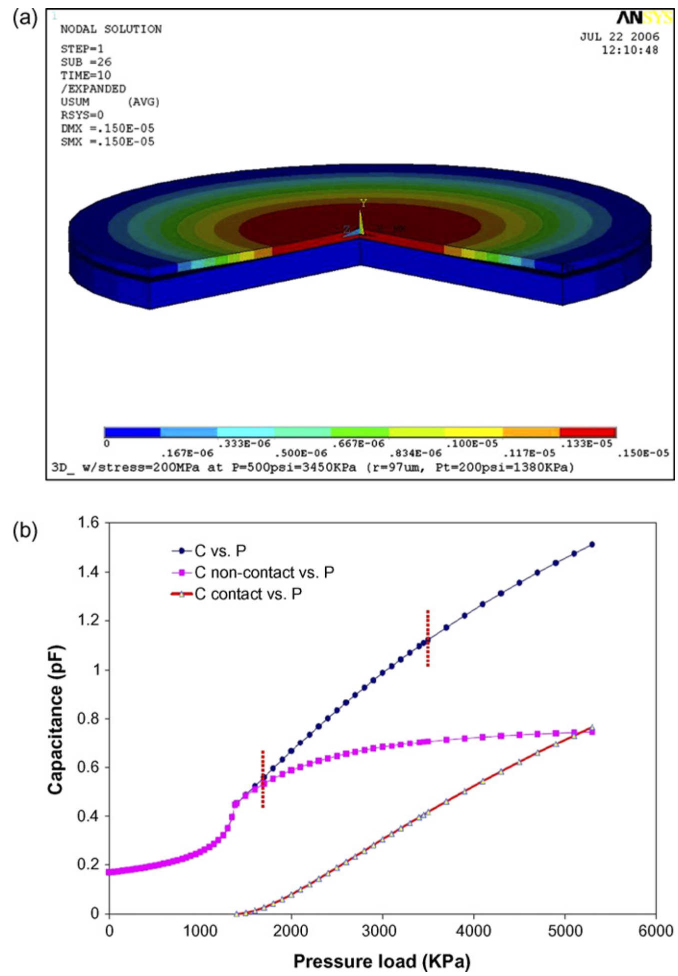

Fig. 2. Sensor modeling results: (a) three-dimensional finite element simulation for contact-mode operation in the pressure range of ∼1.8 MPa (250 psi) to ∼3.5 MPa (500 psi) and (b) linear fit to the model prediction showing a non-linearity of 0.5% (deflection not to scale in (a)).

(i.e., otherwise the same diaphragm thickness and zero-pressure gap) for the pressure range of ∼1.8–3.5 MPa (250–500 psi). The capacitance characteristics presented in Figs. 1b and 2b were calculated corresponding to the diaphragm deflection, which accounts for non-linear deflection behavior, as well as membrane middle-plane stretching and film residual stress. These modeling results demonstrate that acceptable sensitivity and linearity can be achieved for a selected pressure range even when the diaphragm thickness and zero-pressure capacitive gap is fixed by the process. The sensor's model is used to verify the measured performance data by incorporating measured process parameters in place of nominal design values.

The sensor architecture implements a suspended poly-SiC diaphragm with multiple surrounding anchor points and release access channels to facilitate the diaphragm cavity's subsequent wafer-scale release and sealing. Although the diaphragm clamped edge boundary condition used in FEA modeling may seem to be interrupted by release access channels, the ensuing patterned LTO seal ring around the periphery provides