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Design of laser micromachined single crystal 6H–SiC diaphragms for high-temperature micro-electro-mechanical-system pressure sensors

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ABSTRACT

A 248-nm, 23-ns pulsed excimer laser was used to micromachine 50 μm thick diaphragms in 6H–SiC wafers. The diaphragms were then subjected to high-pressure (0.7–7 MPa) and high temperature (500 K) tests to obtain the pressure-deflection curves. A finite element model was used to predict the stresses and displacements as a function of temperature and pressure. Model data is in good agreement with experiments. The stresses, strains and displacements were determined in order to facilitate the design of high-temperature micro-electro-mechanical-system pressure sensors.

1. Introduction

Micro-electro-mechanical-system (MEMS) sensors have grown into a multi-billion dollar industry due to their small size, excellent performance, low cost and high volume production. Silicon-based MEMS pressure sensors currently serve large markets for pressure sensing in moderate temperature applications, with the most advanced devices operating up to about 400 K [1]. There is an emerging and growing demand for MEMS pressure sensors to function accurately and reliably at temperatures higher than 700 K in mechanically and chemically harsh environments such as in many energy conversion and emission control applications. For example, MEMS sensors are highly sought after for measuring engine exhaust streams in corrosive, high-temperature environments (>850 K) or monitoring extreme pressures (both high and low) in industrial applications. Specifically, Siemens Westinghouse Power Generation is seeking technologies that produce sensors for use at 1000 K that should have the potential of being commercially deployed in electric power generation systems in the 1–1500 MW power output range prior to 2015. In the automotive industry, requirements for improved fuel efficiency and reduced emissions over the next 5–10 years create numerous opportunities for such devices. Similarly, energy needs are making additional possibilities for the use of pressure sensors that can operate at higher temperatures and in chemically reactive environments. Some examples are fuel cells (particularly reformers), coal-based power generation plants, and down-hole drilling operations.

Silicon carbide (SiC)-based MEMS pressure sensors can fulfill the requirements of working in hostile and harsh environments such as high temperature, high-pressure, high vibration, high noise, or corrosive chemicals due to SiC's exceptional mechanical, electrical, chemical and thermal properties [2]. SiC also exhibits excellent piezoresistive effect and is compatible with complementary metal oxide semiconductor (CMOS) process (allowing for integration with CMOS circuits). In fact, 6H–SiC piezoresistive pressure sensors have already been fabricated by using a combination of deep reactive ion etching (DRIE) and electrochemical etching methods and are capable of operating at 650 K and pressures ranging from 0.175 MPa to 7 MPa [3]. Despite such benefits, etching of SiC and fabrication of high-temperature contact and pad materials remains to be tedious and time-consuming.

Fig. 1 shows a cross-sectional view of a pressure sensor that we have designed. It consists of: (a) a MEMS diaphragm integrated with SiC-piezoresistor; (b) electronics chip; and (c) AlN packaging. It is based on the piezoresistive effect which is the change in electrical resistance of the material due to applied mechanical stress. For proper functioning of the sensor, it is vital to calculate the relationship between stress distribution in the elastic diaphragm and pressure/temperature. The performance of a sensor is strongly influenced by the size of diaphragm particularly thickness [4]. Mechanics shows that thin diaphragms that act like thin plates subjected to distributed load have greater effect on the maximum deflection than on the maximum bending stress. Generally, at low operating pressures ($P < 30$ kPa), thin diaphragms are needed while at higher operating pressures ($P > 35$ MPa) the use of thicker diaphragms is recommended [5]. The shape of the diaphragm also influences the maximum bending stress and deflection. Circular diaphragms result in excessive deflection but lower stress.

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