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Comprehensive assessment of MEMS double touch mode capacitive pressure sensor on utilization of SiC film as primary sensing element: Mathematical modelling and numerical simulation

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A R T I C L E I N F O

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A B S T R A C T

Capacitive Pressure Sensors have consistently been an indispensable application of MEMS (Micro Electro Mechanical Systems) because of their utility and precision. Silicon has proven to be a dominant material in MEMS based sensor design but it is unfit for applications operating in harsh environmental conditions. Silicon Carbide is a justified replacement to Silicon in these conditions due to its solitary attribute of robustness and high temperature tolerance. This work introduces a Silicon Carbide and Aluminum Nitride based DTMCPS (Double Touch Mode Capacitive Pressure Sensor) with a substrate notch. Condensed yet exhaustive step by step mathematics of key performance parameters have been detailed for the sensor under study. This is done to provide a detailed understanding of the underlying physical and mathematical principles. It also aims to provide a fast analysis model for prototyping the sensor to bypass the need for bulky simulation software. A Finite Element Analysis (FEM) analysis for the design was conducted using COMSOL and the results agree with the mathematical model. It is evident from numerical simulation and the FEM analysis that the proposed sensor provides better performance than comparable designs reported in literature.

1. Introduction

Since the early development of MEMS, sizeable electromechanical sensors have been replaced by smaller miniaturized scale sensors [1]. MEMS technology has been remarkably fruitful in the physical sensing of environmental conditions and has hence yielded a vast range of inexpensive devices like microphones, strain gauges, accelerometers, pressure sensors etc. [2,3]. Capacitive Pressure Sensors acquire an advantage over micromachined Piezoresistive pressure sensors because of low power consumption, IC Compatibility, free from temperature effects and high sensitivity [4,5]. They work on the principle of varying capacitance based on the pressure applied on the diaphragm, which is a flexible electrode closely placed near a substrate that rests on another electrode. As pressure is applied, the distance between the electrodes differs, hence affecting the capacitance [6]; as given in Eq. (1)

$$C = \frac{A\varepsilon}{d} \tag{1}$$

At present, the essential material utilized as a part of MEMS remains as Silicon (Si) [7] since it's micro fabrication strategies perfectly align with the microelectronics processing. Notwithstanding, an expanding interest for MEMS Pressure sensors for severe environmental conditions applications like the oil industry, gas turbine control, combustion processes etc. silicon has not been feasible. Thus, Silicon Carbide (SiC) is perceived as a great possibility for micro sensor applications in harsh environmental conditions because of its one of kind properties which incorporates high hardness, wear resistivity, mechanical robustness, good thermal stability, chemical inertness, high thermal conductivity and high critical electric field [8,9]. These excellent properties can be assumed to be derived from high strength of Si—C bond [10]. SiC exists in large number of polytypes. There are more than 100 of these polytypes known, yet the dominant part of innovative work has focused on three: 3C, 6H and 4H. 4H and 6H hexagonal structures are generally used to make the bulk of substrates for Pressure sensors because of their general predominant material properties [11]. The 3C—SiC polytype is more typical for MEMS based sensors because of the fact that it can be

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developed on Si wafers; therefore it reduces the net wafer cost. In this work, we have used 3C—SiC as the fabrication material for the diaphragm and 6H—SiC for the substrate.

SiC possesses a wide band gap, which as a result lessens the quantity of electron-hole pair formation due to the thermal activation process across the band gap and thus permits it to work efficiently in high temperature conditions. We have used Aluminum Nitride (AlN) as the insulation layer because of its compatible properties. It has good thermal shook resistance, environmental stability, high electrical resistivity, high mechanical strength and nontoxicity. AlN is steady at high temperatures and has a reasonably high melting point of 2800 °C [12]. It is also impervious to assault from mineral acids, solid alkalis and most liquid salts. Moreover, it is most critical that AlN can be placed on a surface of 6H—SiC because of comparable crystal structures, that is, it's coefficient of thermal expansion closely matches with that of SiC.

Despite the fact that the Table 1 demonstrates that BeO has a higher thermal conductivity than AlN at room temperature, AlN has a comparable and considerably higher conductivity at raised temperature [20, 21].

It was found that AlN is a dielectric, and SiC is a wide band gap semiconductor. Thus, the juxtaposition of SiC—AlN is turning into a novel other option to Si—SiO_2 as a predominant structure at present. In addition, the SiC—AlN structure's invaluable guarantee for MEMS is likewise directed by the great crystallochemical similarity amongst SiC and AlN, which is self-explainable as the lattice mismatch between them has found to be just 1%.

In literature, it has already been discussed that Silicon DTMCPS (Double Touch Mode Capacitive Pressure Sensor) is more efficient and accurate than STMCPS (Single Touch Mode Capacitive Pressure Sensor) for pressure measurement [13–18]. To accomplish even more precise, accurate and enhanced linear operating range over the reported literature, a DTMCPS utilizing SiC—AlN—SiC structure has been proposed in this work. Needless to say that DTMCPS aided with SiC film allows the sensor to be operated in high temperature and harsh operating environment.

This article provides compact but complete step by step mathematics of the of key performance parameter i.e. Capacitance and Sensitivity for Silicon Carbide DTMCPS. The fabrication process is briefly elucidated in Section 6. The subsequent sections provide the numerical simulations and it is evident that DTMCPS(SiC) provides better performance than already reported STMCPS(Si) [16], STMCPS(SiC) [19], DTMCPS(Si) [17]. Appending the advantages of the sensor it is worth mentioning that simulation parameters selected are in accordance with small deflection theory of thin plate and the chosen numerical values of the parameters outperform the latest result reported in literature [19].

2. Elementary structure of DTMCPS

The structure shown in Fig. 1 is known as Double Touch Mode Capacitive Pressure Sensor. It consists of a flexible diaphragm which acts as one of the two electrodes and the substrate as the second [17]. They are covered with AlN which acts as the insulation layer, which prevents the short circuit between the two electrodes. The differential pressure between the external environment and the internal cavity tends to increase when pressure is applied on the diaphragm.

Table 1
Basic material properties of AlN, Al_2O_3 & BeO.

Properties	Ceramics		
	AlN	Al_2O_3	BeO
Thermal Conductivity(W/mK)	200	20	250–300
Dielectric Strength (kV/cm)	140–170	100	100
Dielectric Constant (@ 1 MHz)	8.8	8.5	6.5
Tan G ($\times 10^{-4}$ @ 1 MHz)	5–10	3	5
CTE ($\times 10^{-6}$/qC) (25–400 qC)	4.5	7.3	8
Density (g/cm^3)	3.3	3.9	2.9
Flexure Strength (MPa)	300–500	240–260	170–230

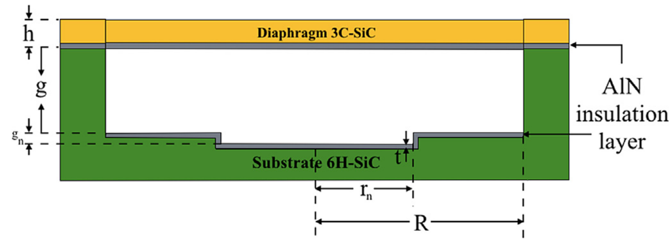

Fig. 1. Cross sectional view of double touch mode capacitive pressure sensor.

3. Working of DTMCPS

As external pressure is applied on the diaphragm, it starts bending towards the substrate thereby decreasing the distance between the two electrodes and results in the increase of capacitance as shown in Eq. (1). A DTMCPS is said to be working in two modes: Normal Mode and Touch-Mode. Touch Mode is further classified into three regions- Transition Region, Linear Region and Saturation Region [13].

Normal mode operation is when the diaphragm doesn't touch the substrate. At the point when the external pressure increases to the Touch Point Pressure (TPP), TPP1 is said to be achieved and the diaphragm makes first contact with the base of the sealed cavity as shown in Fig. 2, causing a precarious non-linear increase of capacitance with the external pressure (Transition Region).

With a further increase in pressure, the diaphragm touches the first notch of the substrate (conversely second notch of the sensor), at this point TPP2 is said to be achieved as shown in Fig. 3.

As the Pressure is additionally expanded into the touch mode (Fig. 4) adequate contact is required to linearize the capacitance with the applied pressure.

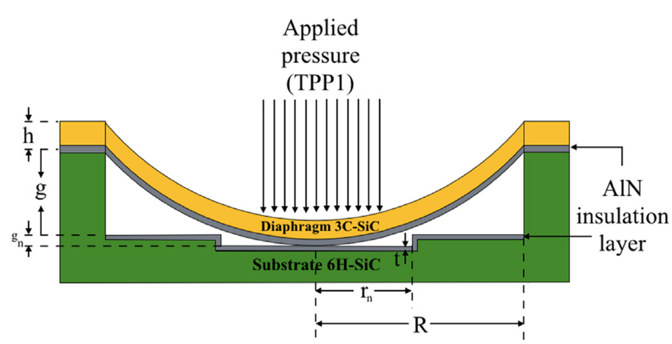

Fig. 2. At the point albeit external pressure equals touch point pressure (TPP1).

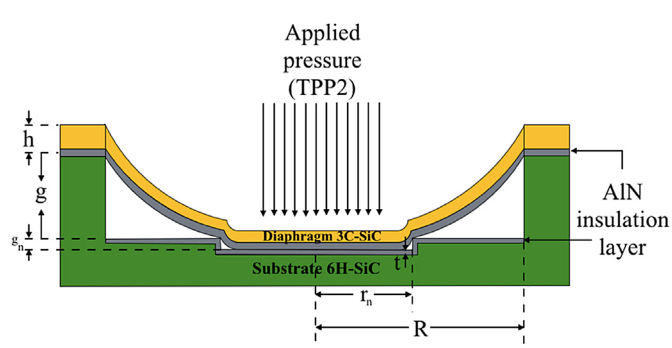

Fig. 3. Touch point pressure(TPP2) is realized.