Performance Analysis of MEMS Capacitive Pressure Sensor with Different Dielectrics

Sachin Kumar, Rashmi Ranjan Kumar, and Saurabh Kumar Pandey

Abstract In this manuscript, two Micro-Electro-Mechanical System (MEMS) capacitive pressure sensors with different dielectrics are designed and simulated with device simulation software. This paper describes the performance analysis of a capacitive pressure sensor working on the electromechanics interface. The sensors modeled have a square diaphragm membrane. Here we have used silicon carbide (SiC) as a diaphragm material. ZnO radical nanoclusters (R-ZnO) and $BaTiO_3$ (BT) nanoparticles are embedded into polyvinylidene fluoride (PVDF) (i.e., R-ZnO/BT/PVDF) and Ag@TiO_2 fillers into polytetrafluoroethylene (PTFE) (i.e., Ag@TiO_2/PTFE) as dielectric material. We have investigated the different performance parameters for the MEMS capacitive pressure sensor such as the total displacement, capacitance, sensitivity, etc., for the optimal design of pressure sensors. These pressure sensors will be used in a harsh environment involving high-temperature applications.

Keywords SiC · R-ZnO · BT · PVDF · Ag@TiO2 · PTFE · Sensitivity

1 Introduction

In this modern world, the demand for pressure sensors application in the latest gadgets such as automobile, bio-medical, industrial, and commercial applications has extremely increased [1–5]. Due to the latest research in the field of microscale and nanoscale fabrication technology, MEMS pressure sensors are being fabricated for the pressure range from ultra-low pressure to very high pressure [6]. This helps to reduce the product cost per unit. The importance of the MEMS pressure sensor

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S. Mukherjee et al. (eds.), *Computational Mathematics, Nanoelectronics, and Astrophysics*, Springer Proceedings in Mathematics & Statistics 342,
https://doi.org/10.1007/978-981-15-9708-4_8

is gaining interest due to lightweight, high reliability, high sensitivity, integrated to IC fabrication process, low power consumption, and small interface features [7–9]. Optical, capacitive, piezoresistive, resonance, acoustic transduction standard is utilized as a part of the ongoing work in the advancement of MEMS pressure sensor designing and manufacturing [10]. Among capacitive pressure, sensor rules were generally adopted in different works. As we know that most of the MEMS capacitive pressure sensors are based on silicon material which is not suited for the extremely high-temperature environment due to the limited operating of mechanical and electrical properties that can be degraded below the temperature of 300 °C [11]. So, we use silicon carbide material to improve the performance of a MEMS capacitive pressure sensor, which shows the emphasis on mechanical and thermal stability for its fabrication and makes it possible to operate in high-temperature applications.

The capacitive pressure sensor works on the principle of change in capacitance with the applied voltage or pressure [12]. These sensors have a sensing element of the constant area and give a response when pressure is applied to this area (e.g., gas pressure, fluid pressure, etc.). When we apply a force, the internal diaphragm of the pressure sensor gets deflected. The deflection of the diaphragm is quantified and converted into an electrical replication. This allows the pressure to be monitored by microprocessor, microcontroller, programmable logic controller (PLC), and computers along with the similar electrical instrument. So, the area of MEMS capacitive pressure sensor application is expanding, hence it is necessary to audit the way of innovative improvement and further imminent of MEMS pressure sensor.

The simulation and output study results of the designed pressure sensor are analysis using COMSOL 5.3 Multiphysics simulation software. COMSOL is a Multiphysics simulation software which provides conventional physics-based user interface IDE and unified workflow for electrical, mechanical, fluid, and chemical applications. The performance parameters used in this paper are the following.

Total Displacement—Total displacement is defined as the displacement of diaphragm membrane with a change in the applied pressure.

Total Capacitance—Total capacitance is defined as the capacitance of the model with change in the applied pressure.

Sensitivity—In this paper we analyze pressure sensitivity and temperature sensitivity of the model. Pressure sensitivity is defined as a change in capacitance with respect to change in the applied pressure [13], and temperature sensitivity is defined as a change in capacitance with respect to change in the operating temperature.

In this paper, we specially focused on the performance comparison of the MEMS capacitive pressure sensor using two different polymer composite materials like R-ZnO/BT/PVDF and Ag@TiO_2/PTFE, respectively, as a dielectric material. Silicon carbide has been used as diaphragm material. This paper is divided mainly into four sections. The second section describes the device structure and property of material used and the third section explains the different measurements and analyses carried out in the work. The fourth section presents the final conclusion.

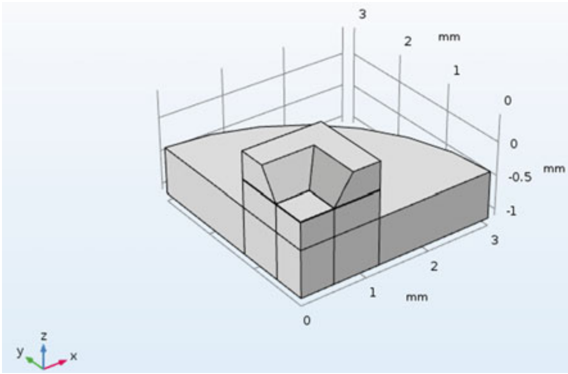

Fig. 1 3D COMSOL model of MEMS capacitive pressure sensor

2 Research Methodology

2.1 Device Structure

The 3D device structure of pressure sensor is shown in Fig. 1. Since the geometry of the model is symmetric so we have used only one by fourth of the geometry and symmetry boundary condition. The pressure sensor is part of a silicon carbide die that has been bonded to a metal plate at 70 °C. The design model is operating at room temperature.

It consists of silicon carbide, steel AISI 4340, and dielectric material. The polymer-matrix composition material that shows high-dielectric permittivity constant has received increasing interest recently for varied potential application in high charge storage electrical device [14]. Here, we have considered R-ZnO/BT/PVDF and Ag@TiO_2/PTFE as two different dielectric materials.

Property of SiC—SiC is a semiconductor material containing silicon (Si) and carbon (C). It is originally made by electrochemical reaction of silicon sand and carbon at extreme temperature. SiC consists of a tetrahedral of carbon and silicon atom with robust bounds within the space lattice. This produces very strong material. SiC isn't attacked by any acids or alkalis or liquefied salt up to 800 °C. It exhibits high thermal conductivity (20.7 W/m.K), low thermal expansion, and high strength, which make this material to have extraordinary thermal shock characteristics. It also has a low density and high elastic module. In air, SiC forms a protective SiO_2 coating at 1200 °C. Its melting point is about 1750 K. Properties of SiC that we have used for modeling are summarized in Table 1.

Ag@TiO_2&PTFE—Composition of core-shell Ag@TiO_2 nanoparticles and PTFE is used to get high-dielectric composites. This composite exhibits higher dielectric permittivity constant than of pure form of PTFE. Its dielectric loss for the composition containing 70% vol. of Ag@TiO_2 as a filler, at 10 MHz is about 0.005. Its dielectric loss is stable and remains small when the frequency reaches 1 MHz [15].

Table 1 Property of silicon carbide

Property	Value with unit
Young's modulus	137 GPa
Poisson's ratio	0.37
Density	3217 kg/M^3
Relative permittivity	9.66
Coefficient of thermal expansion	4.5e−6 K^{-1}

Table 2 Relative permittivity of used dielectric material

Dielectric	Value
Ag@TiO_2/PTFE	240
R-ZnO/BT/PVDF	175

R-ZnO/BT/PVDF—It is three-phase-percolative composition with ZnO radical nanocluster (R-ZnO) and $BaTiO_3$ (BT) nanoparticles implanted into polyvinylidene fluoride (PVDF). This composition exhibits small dielectric loss, large dielectric permittivity constant, and good thermal stability. These properties make the three-phase-percolative composition especially attractive for practical applications. The dielectric loss is about 0.45 [16] (Table 2).

3 Results and Discussion

The MEMS capacitive pressure sensor has been investigated with applied pressure from the range 0 Pa to 25 kPa. We have used different plots to show the variation of different analyzing performance parameters to identify the optimum one. We have also studied the effect of operating temperature from the range 290–1000 K to investigate the best response for high-temperature applications (Tables 3 and 4).

Capacitance of parallel plate capacitor is given by

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

where ε = Permittivity of the free space.
d = Distance between two plates.
A = Area of the two plates.
K = Dielectric Constant.

From Eq. (1), we have concluded that capacitance is inversely proportional to distance between two plates of capacitor [17]. That means when the distance between the plates decreases it results in increase of capacitance value. Figures 2 and 3 shows the variation average and maximum displacements of the diaphragm membrane as

Table 3 Capacitance comparison for $Ag@TiO_2$/PTFE and R-ZnO/BT/PVDF dielectric material capacitor

Diaphragm material	Dielectric material	Pressure (Pa)	Capacitance (pF)
Silicon Carbide (SiC)	$Ag@TiO_2$/PTFE	0	176.8952
		5000	187.39
		10,000	200.8443
		15,000	219.1571
		20,000	247.219
		25,000	317.2877
	R-ZnO/BT/PVDF	0	128.9425
		5000	136.5702
		10,000	146.3304
		15,000	159.5579
		20,000	179.5823
		25,000	222.6961

Table 4 Pressure sensitivity comparison for $Ag@TiO_2$/PTFE and R-ZnO/BT/PVDF dielectric material capacitor

Diaphragm material	Dielectric material	Pressure (Pa)	Sensitivity (pf/Pa)	Mean sensitivity
Silicon Carbide (SiC)	$Ag@TiO_2$/PTFE	5000	2.1×10^{-3}	3.516×10^{-3} pf/Pa
		10,000	2.69×10^{-3}	
		15,000	3.664×10^{-3}	
		20,000	5.612×10^{-3}	
	R-ZnO/BT/PVDF	5000	1.526×10^{-3}	2.532×10^{-3} pf/Pa
		10,000	1.952×10^{-3}	
		15,000	2.646×10^{-3}	
		20,000	4.004×10^{-3}	

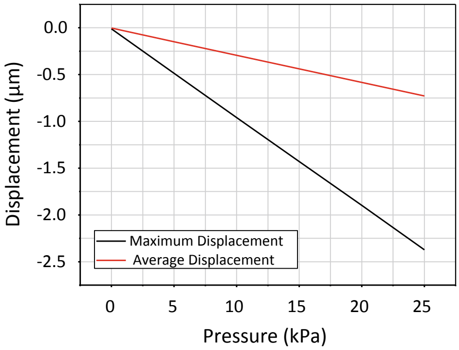

Fig. 2 Displacement and pressure graph for $Ag@TiO_2$/PTFE

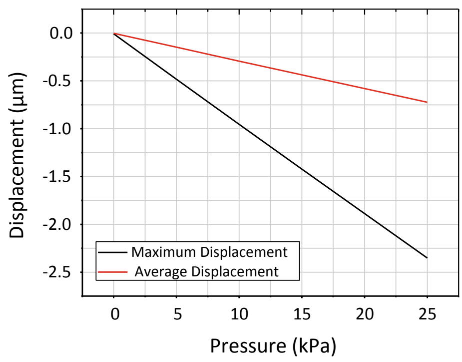

Fig. 3 Displacement and pressure graph for R-ZnO/BT/PVDF

a function of applied pressure for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric material capacitor pressure sensor respectively. When we applied pressure of 10 kPa, the displacement of diaphragm membrane for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric-based sensor from the center is 0.96008 μm and 0.9552 μm, respectively. The average displacement of the diaphragm membrane is 0.29471 μm and 0.29326 μm for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric-based sensor, respectively. These results show that the displacement of diaphragm membrane is more dependent on pressure. So, with increase in pressure, the distance between two plates gets decreased which increases the capacitance.

The displacement of the diaphragm membrane due to applied pressure causes a change in capacitance due to a change in distance between plates of capacitor [17]. Figures 4 and 5 show the variation of capacitance with applied pressure for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric-based sensor, respectively. From graphs, we have concluded that the capacitance of device will increases nonlinearly with increasing in applied pressure. The nonlinear response of graphs due to shear stress and strain distribution on the diaphragm causes complexity in designing the interface circuitry. At an applied pressure of 10 kPa, the capacitance becomes 200.8443 pF and 146.3304 pF for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric-based, respectively. Similarly, when we increase the applied pressure to

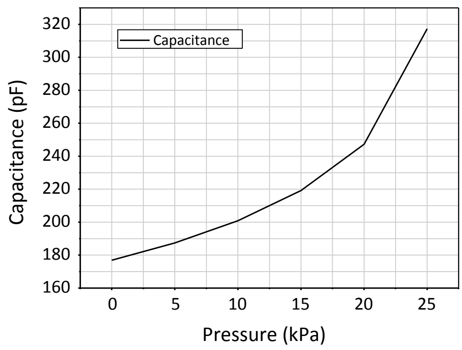

Fig. 4 Capacitance and pressure for Ag@TiO2/PTFE

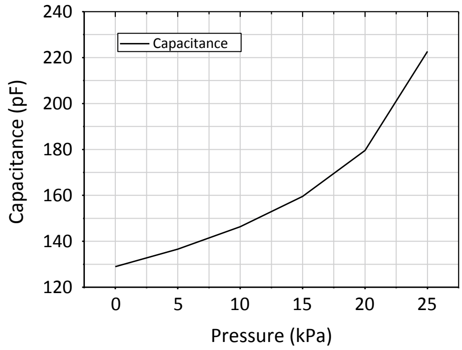

Fig. 5 Capacitance and pressure for R-ZnO/BT/PVDF

20 kPa, the value of capacitance becomes 247.219 pF and 179.5823 pF, respectively. So Ag@TiO_2/PTFE dielectric capacitor sensor gives better results for practical application.

The slope of the plotted curve has been used to measure the pressure sensitivity of the sensors. When we applied 5 kPa pressure, the sensitivity is 2.1×10^{-3} pf/Pa and 1.526×10^{-3} pf/Pa for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric-based sensor, respectively. From the graphs, we have observed that the slope of capacitance changes for Ag@TiO_2/PTFE dielectric-based sensor is steeper as compared to R-ZnO/BT/PVDF dielectric-based sensor. Hence mean pressure sensitivity 3.516×10^{-3} pf/Pa and 2.532×10^{-3} pf/Pa have been obtained for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric material capacitive pressure sensor, respectively.

Figures 6 and 7 show the variation of capacitance with operating temperature for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric-based sensor, respectively. Graphs show that when we applied pressure 20 kPa, the capacitance of a device decreases with an increase in operating temperature. The Ag@TiO_2/PTFE dielectric-based material exhibits a large change in capacitance with increasing operating temperature. This evident that Ag@TiO_2/PTFE dielectric-based MEMS capacitive sensor is capable of functioning for high-temperature and high-power conditions enable producing high-performance enhancement to various varieties of systems and applications.

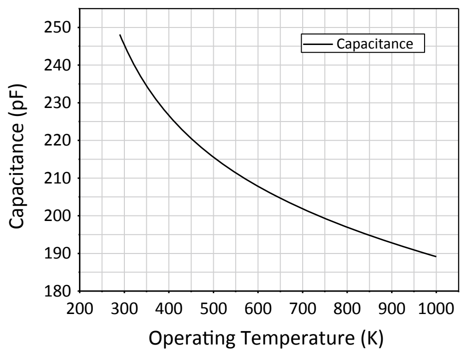

Fig. 6 Capacitance and operating temperature for Ag@TiO_2/PTFE

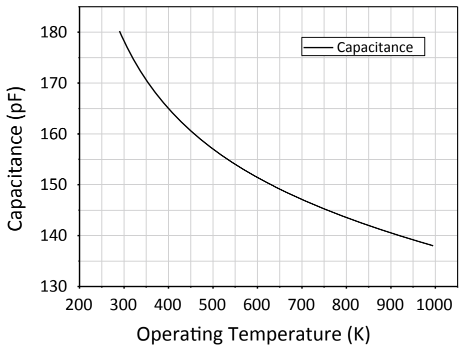

Fig. 7 Capacitance and operating temperature for R-ZnO/BT/PVDF

The temperature sensitivity of the model response is determined by the slope of the curve, which is close to 193.95 $\times$ 10^{-3} pF/K and 277.26 $\times$ 10^{-3} pF/K for Ag@TiO_2/PTFE and R-ZnO/BT/PVDF dielectric-based sensor, respectively. Hence, the temperature sensitivity of Ag@TiO_2/PTFE dielectric material capacitor is better than R-ZnO/BT/PVDF dielectric material capacitor.

4 Conclusion

In this paper, we have designed and analyzed performance parameters of MEMS Capacitive Pressure sensor using device simulation software. The measurement has been carried out for two different dielectric materials, namely, Ag@TiO_2/PTFE and R-ZnO/BT/PVDF. By using SiC and dielectric material performance of MEMS capacitive pressure increase with a maximum capacitance of 317.2877 pF. This is by introducing dielectric material and due to SiC thin film membrane because of its structural integrity of high thermal conductivity and Young's Modulus that can withstand a high operating temperature. Maximum output capacitance using Ag@TiO_2/PTFE dielectric material is given by 317.2877 pF and using R-ZnO/BT/PVDF dielectric material is given by 222.6961pF. The result of the simulation process shows that the capacitive pressure sensor using Ag@TiO_2/PTFE dielectric material shows better sensitivity and capacitance in comparison to others.

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