Silicon carbide on insulator-based pressure sensor for high temperature applications

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Abstract : The work presents modelling and simulation of MEMS based SiC-on-insulator based piezoresistive pressure sensor for high temperature applications. The sensor demonstrated here is a SiC on insulator-based pressure sensor with SiO_2 as an insulating layer. The piezoresistors are SiC material, this is considered in the view that they have good resistance to high temperature. The sensor modeled is a variant to the well-known SOI pressure sensors. The sensor is modeled and simulated using COMSOL Multiphysics. The modeled sensor is compared with Si and SiC based sensor. The voltage sensitivity of SiCOI (Silicon Carbide on Insulator) is 1.2mV/V.MPa compared to 2.8 mV/V.MPa and 2.8 mV/V.MPa for Si & SiC respectively. The sensors are alayzed for the temperature sensitivity. SiCOI has the temperature sensitivity of 8µV/V.^{0}C compared to 32 µV/V.^{0}C & 12.4 µV/V.^{0}C for Si and SiC respectively. Hence it can be observed that SiCOI has the least temperature sensitivity making to the most feasible sensor working at high temperatures. SiC may be considered while designing sensors operating at high temperatures.

IndexTerms - *piezoresistive pressure sensor, mems, COMSOL, silicon and silicon carbide.*

I. INTRODUCTION

Micro Electro Mechanical Systems (MEMS) are devices characterized by both their smaller size and the process of fabrication. MEMS Technology is defined as miniaturized mechanical elements and electromechanical elements that are manufactured utilizing micro fabrication techniques. MEMS devices are manufactured using technique called batch fabrication which is used to create integrated circuits (ICs) and many commercial MEMS products are integrated and packaged together with ICs. Micro sensors, micro actuators, microelectronics and microstructures are the functional elements of MEMS but micro sensors and micro actuators are the most notable elements. Over the past few decades MEMS researchers and developer community has demonstrated large number of microsensors including temperature, chemical species, magnetic fields, etc., and a number of microactuator including micromirror arrays, microvalves, microflaps, micro resonator and many more. Even though these microactuator are smaller in size they often cause effects at the macro scale level. Micro pressure sensors are classified as absolute, differential and gauge sensors and based on transduction mechanisms, mechanism like capacitive, piezoelectric, resonant and piezoresistive have been reported [1]. Amongst the various transduction’s mechanisms, piezoresistive mechanism is widely preferred because of its ease of fabrication, high reliability, better sensitivity, high linearity, simple voltage readout and compensation circuitry [2]. Micro pressure sensors design and miniaturization has been changed considerably after finding the piezoresistivity in silicon and germanium [3-4].

Piezoresistive pressure sensors have been explored largely for many sensing applications. Semiconductor piezoresistive pressure sensors provide high sensitivity then the metal strain gauges, because of their high gauge factors. Piezoresistive sensors explore the piezoresistive effect, where the resistance of piezoresistors changes with applied pressure. Silicon based micro piezoresistive pressure sensors are very popular because of many advantages of silicon. Silicon can be easily doped and controlled to develop required piezoresistors and their resistivity [5]. The sensors now are required to operate in harsh environments in which high temperature is one of the important conditions. Sensors need to be rugged enough to be able to operate at elevated temperatures. Silicon pressure sensors deteriorate at operating temperatures above 150^{0}C, as a result many variants of silicon are developed such as SOI, SiC etc. The SOI and SiC have proven to be capable of withstanding the operating temperatures above 300^{0}C. In this paper we propose a Silicon Carbide on Insulator based piezoresistive pressure sensor operating at high temperature. The sensor modeled is a variant to the well-known SOI pressure sensors. The sensor is modeled and simulated using COMSOL Multiphysics. The modeled sensor is compared with Si and SiC based sensor. The voltage sensitivity of SiCOI (Silicon Carbide on Insulator) is 1.2mV/V.MPa compared to 2.8 mV/V.MPa and 2.8 mV/V.MPa for Si & SiC respectively. The sensors are alayzed for the temperature sensitivity. SiCOI has the temperature sensitivity of 8µV/V.^{0}C compared to 32 µV/V.^{0}C & 12.4 µV/V.^{0}C for Si and SiC respectively.

II. PIEZORESISTIVE PRESSURE SENSORS

Amongst different transduction mechanisms used in pressure sensing, piezoresistive pressure sensing has been used widely [6] Piezoresistive pressure sensor works based on Piezoresistive effect. Pressure sensor when subjected to mechanical strain the effective mass of silicon atoms either increase or decrease which in turn changes the mobility of the silicon carriers, hence the resistance(R) of the material changes which is given by, $\mathbf{R = \rho \mathit{l} / A}$, Where, A-cross-sectional area of the piezoresistive material, l-length of the piezoresistive material, **ρ-** Resistivity of the material. The piezoresistive pressure sensor consists of silicon diaphragm with piezoresistive elements mounted on it. Silicon is used as sensing element. The Piezoresistors are placed in the form of Wheatstone bridge circuit on the They can be used to measure the flow of liquid, the weight or force exerted by one object on another, atmospheric pressure or anything else involving force. A Piezoresistive Pressure Sensor contains several thin wafers of silicon embedded between protective surfaces. The surface is usually connected to a Wheatstone bridge, a device for detecting small differences in resistance. The Wheatstone bridge runs a small amount of current through the sensor. When the resistance changes, less current passes through the pressure sensor. The Wheatstone bridge detects this change and reports a change in pressure.

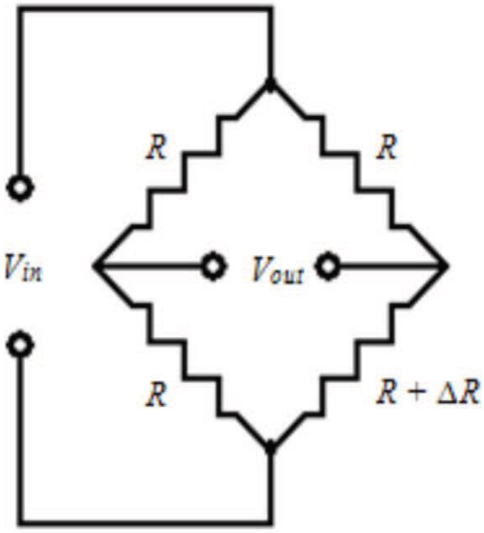

Fig. 1 The Wheatstone bridge

Fig 1 shows Wheatstone bridge consisting of four piezoresistive material labeled as R1, R2, R3 and R4 respectively. Wheatstone bridge is mounted on the diaphragm. When the pressure is applied to the diaphragm, the diaphragm experiences the sheer stress due to which the diaphragm deforms in the direction of pressure imposed. Due to the deformation of the diaphragm, the piezoresistors mounted on the diaphragm in a Wheatstone bridge format stretches. As the piezoresistors stretches, the length increases while the area decreases. If length increases and area decreases, there will be incremental change in the resistance of a piezoresistors and effectively decrease in the output voltage. The output of Wheatstone bridge is given by,

$$V_0 = V_S\left(\frac{R3}{R3+R4} - \frac{R2}{R1+R2}\right) \qquad \textbf{(1)}$$

Where, Vs is the input applied voltage, R1, R2, R3 and R4 are the resistances of the resistors connected in the Wheatstone bridge configuration. Initially all resistances will be same, hence the bridge is said to be balanced and Vo will be 0. When external pressure is applied on the diaphragm, the stress is transferred to the resistors and they undergo change in resistance. This makes the bridge unbalanced and we can observe readable, finite voltage at the output of the bridge. In the work, we have considered the analysis of the sensor at normal temperatures and at high temperatures. Two important parameters such as voltage sensitivity and temperature sensitivity are considered for the performance analysis of the sensors.

III.PIEZORESISTIVE PRESSURE SENSORS

The Sensor model is shown in Fig. 2. The model consists of silicon substrate. The model is back pressurized pressure sensor model. On top the substrate a thin layer of SiO_2 is deposited and four Silicon Carbide piezoresistors are placed and are connected in the Wheatstone bridge configuration. The diaphragm thickness is 10µm and followed by 2µm thick silicon dioxide layer. The piezoresistors are of 140µmX20µmX5µm. These are the optimized dimensions taken from our previous work [7, 8].

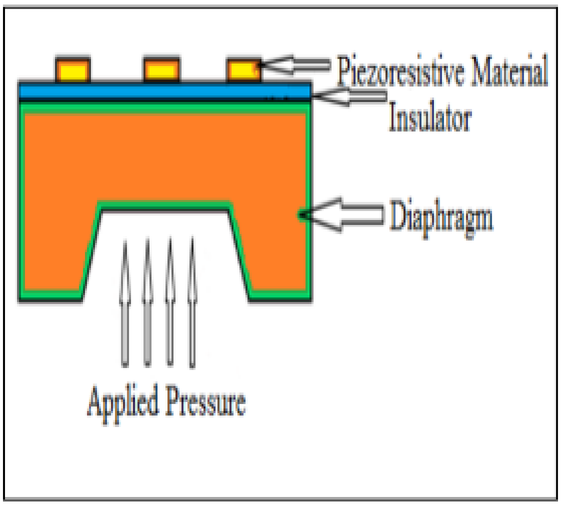

Fig. 2. The sensor models

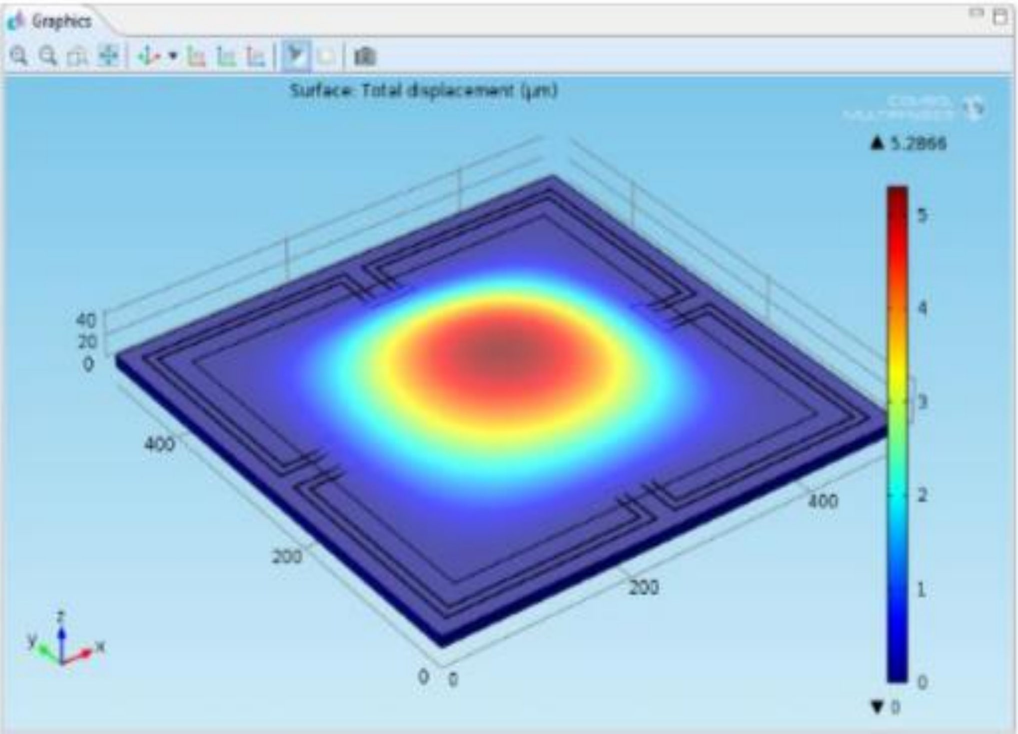

Fig. 3. The simulation model of the sensor

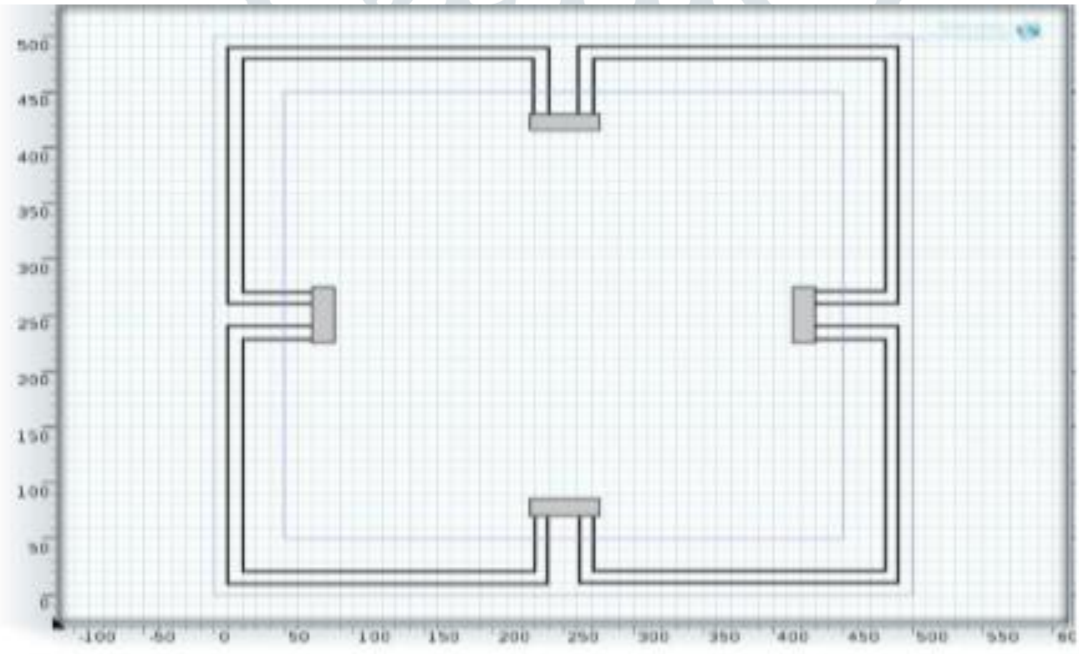

Fig. 4. Top view of the simulation model showing the piezoresistors placement

The simulated model of SiCOI piezoresistive pressure sensor is as shown in fig. 3. Fig. 4 describes the top view of the sensor model showing the piezoresistors placement and the connection. The SiC piezoresistors are placed at the edges of the diaphragm as the edges of the diaphragm experiences maximum stress. The sensor is simulated for a pressure range of 0 to 1MPa. The sensor is subjected to the operating temperature ranging from 0 to 1000^0C. Fine free tetrahedral meshing is applied on the sensor. The model simulated is a FEM analysis model with custom meshing.

The sensors are analyzed for its voltage and temperature sensitivity. Which can be defined as follows:

SENSITIVITY: Sensitivity is the smallest change in the input signal that causes the measuring device to respond. It is the ratio of electrical output from the sensor to its mechanical input. Based on the proper placement of the piezoresistive pressure sensor, the sensitivity can be enhanced. Sensitivity can also be enhanced by manipulating geometrics of the diaphragm. Smaller diaphragms will give greater sensitivity

Voltage Sensitivity

Sensitivity = $\Delta v / \Delta p * vin$

Where, Δv- Voltage difference between two pressure levels, Δp- Pressure difference between the same pressure levels Vin- Input voltage

Temperature Sensitivity

Sensitivity = $\Delta v / \Delta T * vin$

ΔV- Voltage difference between two pressure levels, ΔT- Pressure difference between the same pressure levels, Vin- Input voltage

IV. RESULTS AND DISCUSSION

The results were obtained for the pressure range of 0 to 1MPa, keeping the temperature constant at 25^{0}C. The data obtained are tabulated in table 1 for all the three sensors viz., Si, SiC and SiCOI. The plot of the same is shown in fig. 5. It can be observed for the graph that SiCOI has low output potential as the resistors are placed on an insulator layer, due to which stress transfer to the resistors is reduced. It can be observed that silicon pressure sensor provides better output voltage compared to the other two. Further the sensors are subjected to the high temperature analysis.

In table 2, the simulation results for voltage against temperature is described. The results are taken keeping pressure constant and varying temperature from 0 to 1000^{0}C. The plot of the same is shown in fig. 6. From the plot it can be observed that the voltage drop as a function of increasing temperature is very minimal in SiCOI compared to Si & SiC pressure sensors.

Table 1. variation of voltage against applied pressure at 1MPa

Pressure (MPa)	Voltages in (mV)		
	Si	SiC	SiCOI
0	114.6	131.28	84.4
0.1	116.09	132.4	85.1
0.2	117.5	134.0	85.7
0.3	118.8	135.4	86.4
0.4	120.2	136.8	87.0
0.5	121.1	138.2	87.7
0.6	123.1	139.5	88.3
0.7	124.5	140.9	88.9
0.8	125.9	142.3	89.6
0.9	127.3	143.7	90.2
1	128.7	145.1	90.8

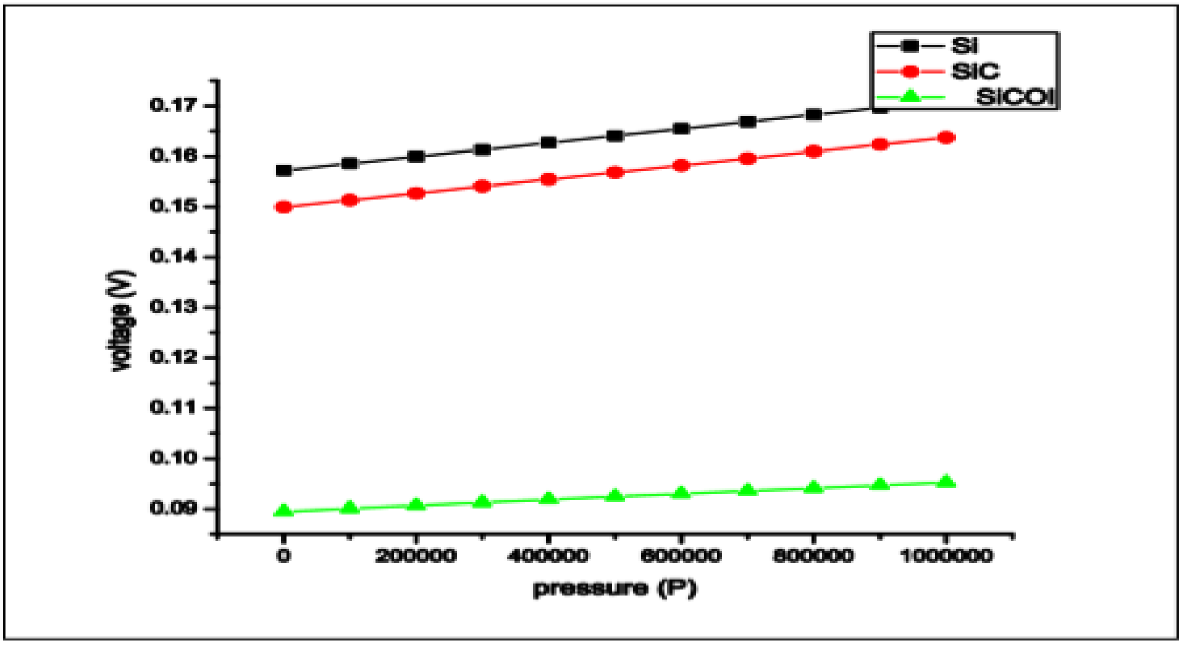

Fig.5, plot of pressure versus voltage at 1MPa

Table 2. Variation of voltage against given temperature values

Temperature (^{0}C)	Voltage (mV)		
	Si	SiC	SiCOI
0	169.9	16.94	95.2
100	171	163.7	95.4
200	161	157	93
300	145.1	151.3	90.8
400	128.7	145.1	87.6

500	112.4	138.89	84.2
600	96.2	132.7	80.5
700	79.8	126.5	76.4
800	62.9	120.3	71.6
900	45.11	114.11	65.99
1000	27.09	107.9	59.09

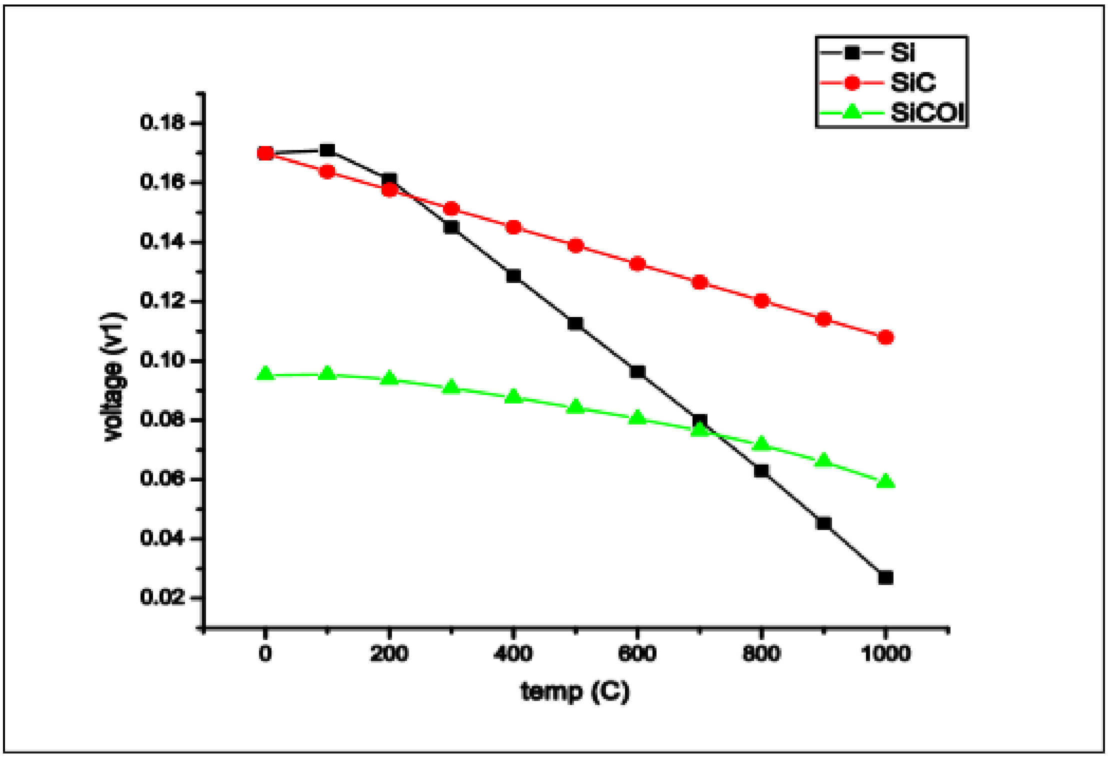

Fig.6, Plot of temperature versus voltage

Sensitivity Analysis

Voltage sensitivity: From the above observation it can be observed that the voltage sensitivity of SiCOI (Silicon Carbide on Insulator) is 1.2mV/V.MPa compared to 2.8 mV/V.MPa and 2.8 mV/V.MPa for Si & SiC respectively.

Temperature sensitivity: The sensors are analyzed for the temperature sensitivity. SiCOI has the temperature sensitivity of 8µV/V.^{0}C compared to 32 µV/V.^{0}C & 12.4 µV/V.^{0}C for Si and SiC respectively. Hence it can be observed that SiCOI has the least temperature sensitivity making it the most feasible sensor working at high temperatures. The sensitivity values are tabulated in the table 3, shown below.

Table. 3, Voltage and Temperature Sensitivities of the sensors

Sensor Type	Voltage Sensitivity (mV/V.MPa)	Temperature Sensitivity (µV/V.^{0}C)
Silicon	2.8	32
SiC	2.8	12.4
SiCOI	1.2	8

V. CONCLUSION

Three pressure sensors viz., silicon, silicon carbide and silicon carbide on insulator are simulated. The results show that silicon has better voltage sensitivity but its performance deteriorate at high temperatures. SiC and SiCOI has low voltage sensitivity but has can withstand high temperature. SiCOI has least temperature sensitivity, which makes it a formidable material in the design of pressure sensors operating at high temperatures. Hence in the design of pressure sensors operating at high temperatures silicon carbide can be used as its performance will not deteriorate as temperature increases.

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