Study and Analysis of Junction Leakage Current in Si & SOI based Micro Piezoresistive Pressure Sensor

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***Abstract*— The work presented here considers the leakage current at the pn-junction in micro piezoresistive pressure sensors. As operational temperature increases the junction leakage current increases, thereafter effecting the sensor performance. This increase in junction leakage current limits the high temperature usage of the sensor. Researchers have used an isolation layer between the junction to minimize the junction leakage current. The work presented here provides the analysis of junction leakage current with and without the use of an insulating layer between the junctions both at low and high temperatures. The work makes a valid attempt to describe the leakage current and its behavior at low and high temperatures. We also present how the use of insulating layer between the junction minimizes the junction leakage current.**

Keywords—Piezoresistive Pressure Sensor, pn-junction, Lakage current, Insulating layer, Temperature.

I. INTRODUCTION

MEMS based pressure sensors are widely in many applications. There are various types of pressure sensors available in the market. These pressure sensors are categorized based on sensing mechanisms. Absolute pressure sensor measures static or dynamic pressure with reference to vacuum. Gauge pressure sensor measures the pressure with respective to the atmospheric pressure. Differential pressure sensor measures the difference between two pressures [1]. In recent years, silicon based piezoresistive pressure sensors fabricated using MEMS technology have been extensively used in commercial and industrial applications. Piezoresistive Pressure Sensors are most commonly used in automobile, aerospace, chemical processing and oils industries for pressure measurements [2]. These sensing environments are considered to be harsh environments. Recently focus has been on design of a piezoresistive pressure sensor for harsh environment, where harsh corresponds to high temperatures well above 300^0C. [3] has shown the effect of temperature on the piezoresistive coefficient of piezoresistive materials such as silicon and germanium. The piezoresistive materials are temperature sensitive and their resistance changes with changing temperature. In its simplest form the piezoresistive pressure sensor has four p-type piezoresistors connected in the form of Wheatstone bridge, embedded/diffused on top of a single crystalline silicon substrate. This process develops a residual stress on the layers which will be different for the piezoresistors and the silicon substrate. These sensors will have zero pressure offset error which keeps on increasing at elevated temperatures [4].

The other problem that the piezoresistive pressure sensors face is the Junction leakage current observed at the junction formed in the sensor. As discussed above that the p-type piezoresistors are embedded on the n-type silicon substrate. This creates a pn-junction and leads to the leakage current which gets higher at high temperatures and thereafter limiting the performance of the sensors. Initially this junction provides a kind of isolation but after 100^0C, the leakage current increases considerably and the performance degrades. The Temperature Coefficient of Resistivity (TCR) is an important parameter of the piezoresistive sensor and is always positive in diffused single crystal resistors. The TCR of piezoresistors affects the sensitivity of the sensor and leads to Temperature Coefficient of Sensitivity (TCS). The TCS gets negative as TCR increases [5]. There are few methods reported in literature to avoid the residual stress, which include careful selection of materials and the tailormade fabrication process. Few papers have reported the use of temperature compensation methods to reduce the zero-pressure offset and the temperature effects on the measurements. The temperature compensation methods include the use of extra resistors on the diaphragm and the use of double/concentric Wheatstone bridge [6-9]. The other method reported are the use of oxide layer in between the resistors and the substrate which provides necessary isolation and reduces leakage current at high temperature. Research have also used materials with wide bandgap such as SiC, Diamond and GaN. But the fabrication of such wide bandgap materials is very difficult and is not matured.

Poly silicon is a material which can withstand high temperature and efforts are made to develop polysilicon piezoresistors on an oxide layer developed on the silicon substrate [5]. The use of polysilicon over oxide layer is limited as the piezoresistive coefficient of polysilicon is small. In recent past Silicon On Insulator (SOI) has been widely explored [10], as SOI has advantage over bulk silicon pressure sensors is that it provides a stable operation when temperature exceeds 125◦C. SOI consists of a buried oxide layer separating piezoresistors and silicon substrate. The buried oxide layer can be used as an etch stop of as insulation layer [11-15]. A brief overview on manufacturing of SOI is described in our previous work [16]. SOI technology is costlier and difficult to customize. In this work we present the analysis of junction leakage current in Silicon and SOI based micro piezoresistive pressure sensors. There has been lot told about the leakage current but we find very little in the literature where this issue has been addressed with valid results. As the junction leakage current plays a very significant role in defining the performance of the sensor, we find it very important that we explore and analyze it. Therefore, in the paper, we present the analyses and behavior of the leakage current in the presence and in the absence of oxide layer.

II. DESIGN & SIMULATION OF SI AND SOI SENSORS

The pressure sensor design consists of piezoresistive elements which are placed on square diaphragm. Piezoresistor are placed on high stress area, which are at the center of each edge. All four resistors are interconnected using connecting line as shown in fig 2.1.

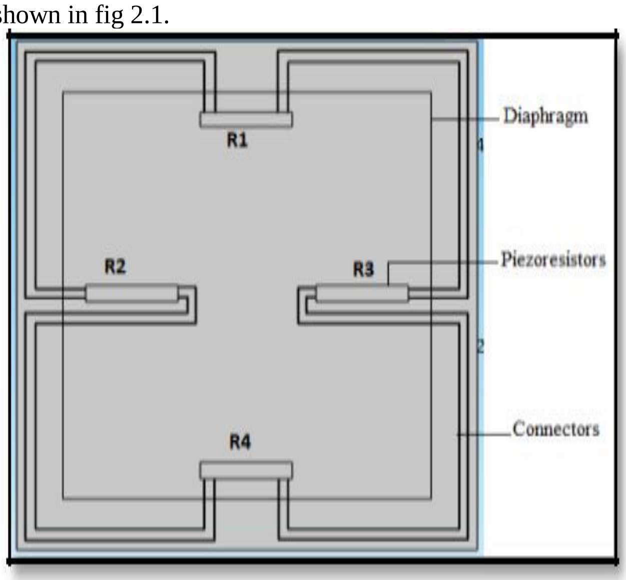


Fig.2.1 Proposed model of a Piezoresistive Pressure Sensor.

The sensor model, four p-type piezoresistors R1, R2, R3 and R4 are implemented on the diaphragm. The sensor has a diaphragm of length 400µm, width 400µm, and height 10µm on n-type substrate. Piezoresistors are of length 100µm, width of 10µm and 5µ in thickness. The same model with the same dimensions is used to develop SOI model. Where the buried oxide layer is silicon dioxide with thickness of 2µm. The side view of the SOI model showing the oxide layer is presented in fig. 2.2.

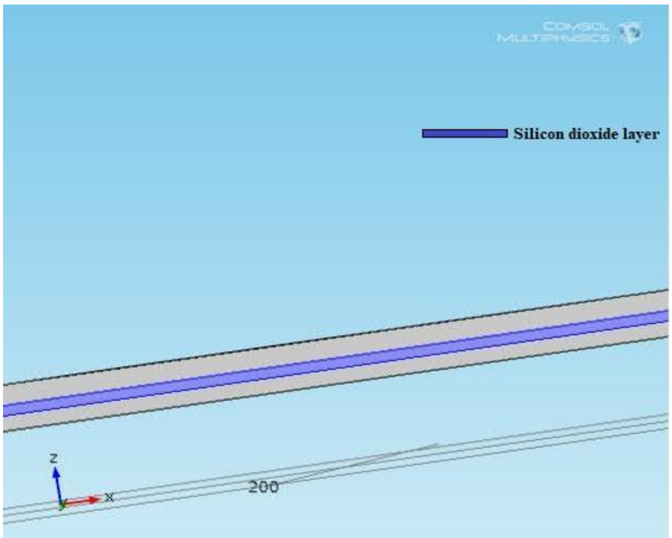


Fig: 2.2. SOI model showing oxide layer

The dimensions of the sensors designed are optimized from our previous work [17, 18]. The dimensions are mentioned in Table 2.1. Material properties used are mentioned in Table 2.2.

TABLE 2.1. DIMENSIONS OF THE SENSOR MODELS

NAME	TYPE	LENGTH	WIDTH	THICKNESS
Substrate	n-type silicon	500µm	500µm	40µm
Diaphragm	n-type silicon	400µm	400µm	10µm
Oxide	SiO_2	500µm	500µm	40µm
Piezoresistors	p-type	140µm	10µm	5µm

TABLE 2.2. DIMENSIONS OF THE SENSOR MODELS

MATERIAL PROPERTIES	N-TYPE SILICON	P-TYPE SILICON	SIO_2
Youngs Modulus	160e9	160e9	170e9
Poission's Ratio	0.22	0.22	0.17
Density (Kg/m^3)	2330	2330	2200

Pressure sensors typically consist of a thin diaphragm/beam, which when subjected to external pressure deforms due to stress. Using appropriate transduction mechanism, the deformation is converted into a readable potential. The sensor models used for simulation are shown in Fig.2.1. & Fig. 2.2. The sensors use piezoresistive effect of materials as the transduction mechanism. The sensor dimensions used for simulation are mentioned in Table 2.1. Simulation is done using COMSOL Multiphysics. The sensors are analyzed for displacement, output voltage and most importantly the junction leakage current. The simulation results are validated using the theoretical equations. The equation used to validate the displacement of the diaphragm is given in equation 1.

$$D = \frac{0.01512(1-V^2)Pa^4}{Eh^3} \quad (1)$$

Where, 'P' is applied pressure, 'a' is side length of the diaphragm, 'E' is Young' modulus of silicon, 'h' is thickness of the diaphragm and 'V' is Poisson's ratio of silicon.

The output voltage depends on the bias voltage to the bridge and the and pressure applied to the diaphragm. Equation 2 is used to measure the output voltage.

$$V_{out} = \frac{Pa^2(1-v)\pi_l}{h^2} \quad (2)$$

Where, π_l is Piezoresistive coefficient of piezoresistors.

The reverse saturation current or reverse leakage current is given by using equation (3)

$$I_s = qA(\frac{D_n n_{po}}{Wp} + \frac{D_p p_{no}}{Wn}) \quad (3)$$

Where, q is charge, A is cross sectional area of diaphragm, D_n and D_p are diffusion coefficients of minority carriers, n_{po} and p_{no} are equilibrium concentration of minority carriers, W_p and W_n are width of p-type and n-type Silicon. The meshed model of the piezoresistive pressure sensor is shown in Fig. 2.3. Adaptive meshing is employed to take care of the smallest element size. The edges and connector corners are carefully meshed in order to avoid void element meshing.

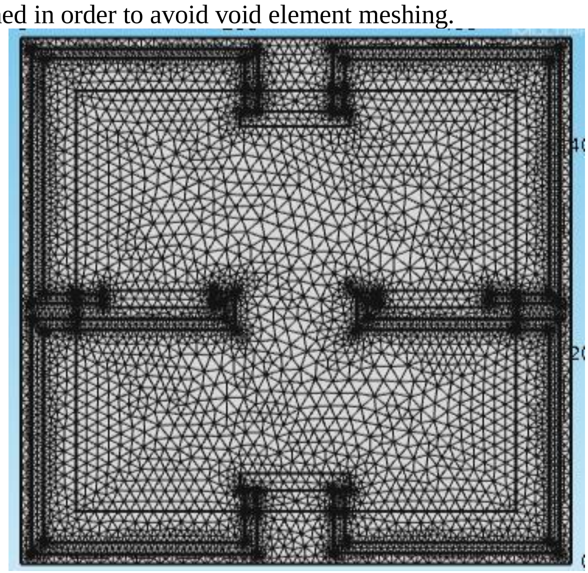


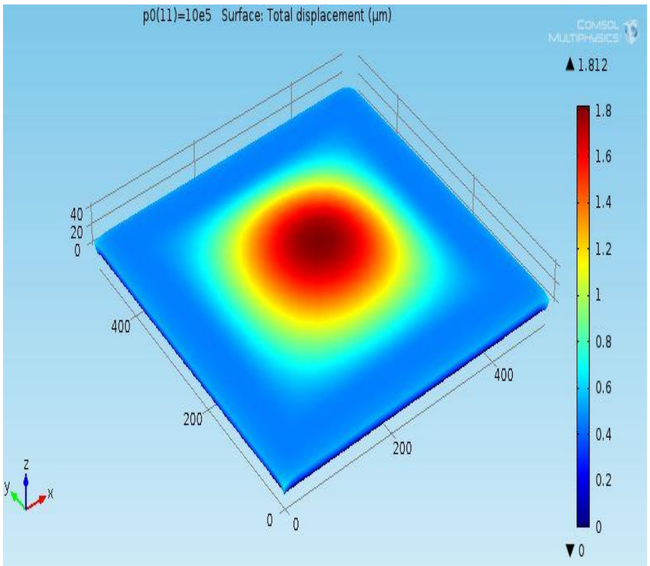
Fig.2.3. Meshed model of the sensor

III. RESULTS AND DICUSSION

In this section simulation result of Micro Piezoresistive sensor with SiO2 Layer and without SiO2 layer are discussed. A Pressure ranging from 0 to 1000KPa is applied on both sensors. Parameters such as total displacement, electrical potential and leakage current are discussed for the two sensors.

3.1. Displacement & Voltage Analysis

Fig. 3.1. & Fig. 3.2. shows the displacement plots for both the sensors respectively. From figures it can be observed that the displacement of the sensor with SiO_2 layer is less than that of the sensor with no SiO_2



ig.3.1 Deformation of Piezoresistive Pressure Sensor without SiO_2 layer

Sensor without the SiO_2 layer shows larger displacement compared to the one with the SiO_2 layer.

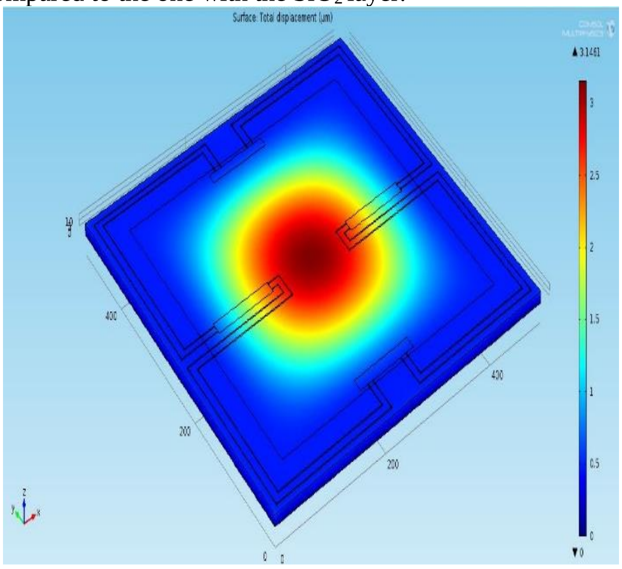


Fig.321 Deformation of Piezoresistive Pressure Sensor with SiO_2 layer

TABLE. 3.1. SIMULATED DISPLACEMENT AND VOLTAGE VALUES OF MICRO PIEZORESISTIVE PRESSURE SENSOR WITH SIO2 LAYER

Applied Pressure (KPa)	Total displacement(µm)	Electric Potential(mV)
0	0	374.70
100	0.12	398.41
200	0.24	421.94
300	0.36	445.31
400	0.48	468.52
500	0.61	491.55
600	0.73	514.44
700	0.85	537.17
800	0.97	559.74
900	1.09	582.15
1000	1.22	604.43

Figure 3.3. shows Displacement values 0µm to 1.220µm for Micro Piezoresistive Pressure Sensor with SiO2 and also from

0µm to 2.6296µm for Micro Piezoresistive Pressure Sensor without SiO2 when pressure ranges from 0KPa to 1000KPa. The overall graph indicates that as pressure increases deformation also increases. The results for the output potential for both the sensors are presented in Table 3.2 & Table 3.3. The same is plotted in Fig. 3.4.

Figure 4.3 shows Electric Potential values 2.354.80mV to 2565.84mV for Micro Piezoresistive Pressure Sensor with SiO2 and also from mV to mV for Micro Piezoresistive Pressure Sensor without SiO2 when pressure ranges from 0KPa to 1000KPa. The overall graph indicates that the potential is linearly increasing with respective to the applied pressure

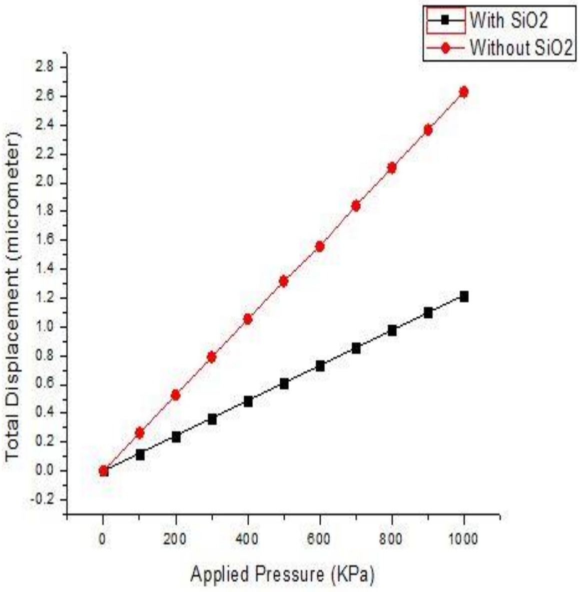


Fig.4.2 Applied Pressure versus Total Displacement

TABLE. 3.2. SIMULATED DISPLACEMENT AND VOLTAGE VALUES OF MICRO PIEZORESISTIVE PRESSURE SENSOR WITHOUT SIO2 LAYER AND WITHOUT SIO2 LAYER

Applied Pressure(KPa)	Total displacement(µm)	Electric Potential(mV)
0	0.6	409.53
100	0.78	417.40
200	1.04	425.13
300	1.3	432.73
400	1.57	440.20
500	1.83	447.55
600	2.1	454.77
700	2.35	461.89
800	2.62	468.88
900	2.88	475.76
1000	3.15	482.54

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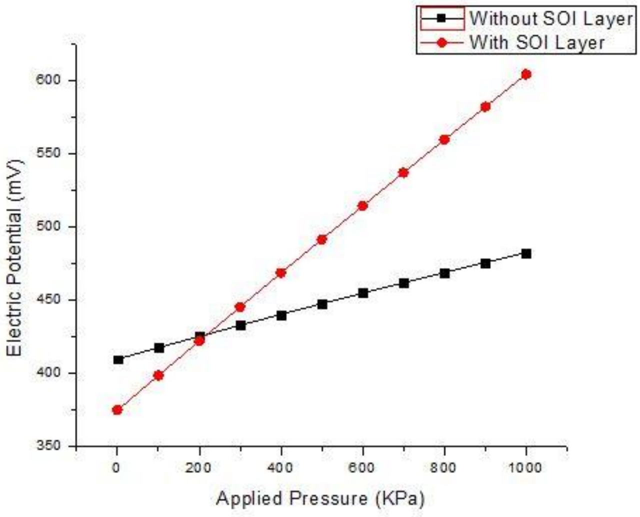

Fig. 3.4. Voltage plot of both the sensors

3.2. Junction Leakage current Analysis

In this section we present the junction leakage current analysis. The doping concentration is taken as 1e16 and the temperature is varied and the corresponding behavior of the junction leakage current is analyzed. The junction leakage current values for both the sensors is tabulated in Table 3.3.

TABLE 3.3. SIMULATED LEAKAGE CURRENT VALUES OF MICRO PIEZORESISTIVE PRESSURE SENSOR WITH SIO2 LAYER AND WITHOUT SIO2 LAYER FOR DOPING CONCENTRATION 1E16

Temperature (In degrees Celsius)	**With SiO2 Layer Leakage Current (µA)**	**Without SiO2 Layer Leakage Current (µA)**
0	33.65	39.07
100	42.96	51.30
200	59.44	75.06
300	96.95	110.05

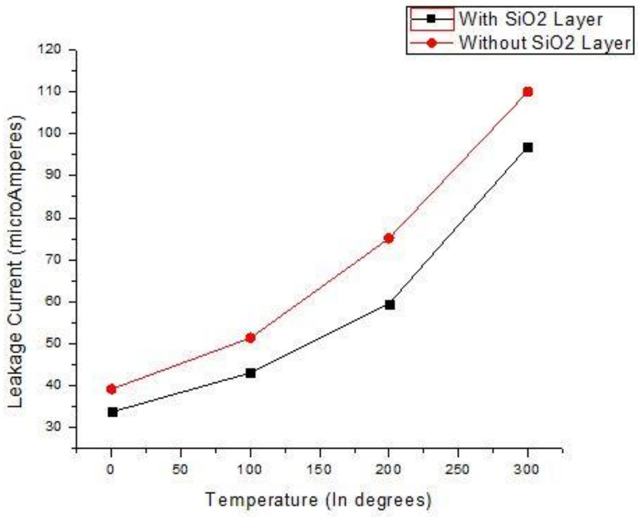

Fig.3.5. Temperature versus Leakage Current

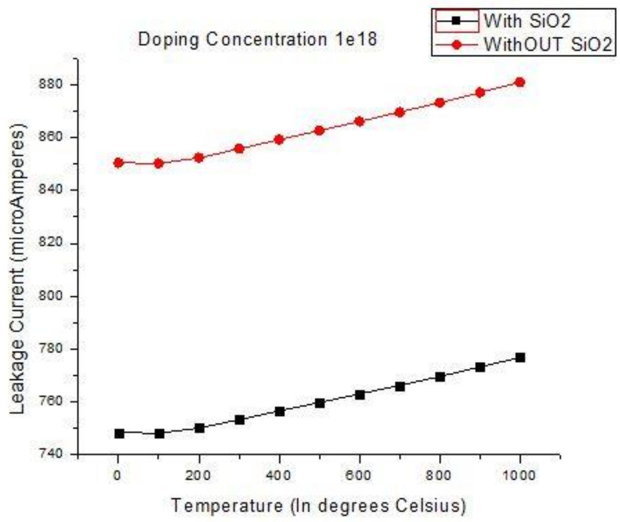

Fig.3.6. Temperature versus Leakage Current

Figure 3.5. & Fig. 5.6, shows Applied Pressure versus Leakage current for Doping Concentration 1e16 and 1e18 respectively. Leakage current values 33.655µA to 35.095µA for Micro Piezoresistive Pressure Sensor with SiO2 layer and also for 39.077µA to 40.681µA for Micro Piezoresistive Pressure Sensor without SiO2 when temperature ranges from 0◦C to 1000◦C with applied pressure is 1000KPa which is constant for all temperature values. The graph indicates as temperature increases the leakage current also increases. But the effect of temperature on the output of sensor with SiO2 layer is much small compared to the sensor without SiO2 layer.

IV. CONCLUSION

In the paper we present the analysis of junction leakage currents for micro piezoresisitve pressure sensors with and without the insulation layer. The leakge current on both the sensors are analysed for diffenrent temperatures. The results shos that the snesor with insulation layer performes better at high tempeartrue. Use of different insulation layers in the design of the sensor makes it possisble to operatre the snesors at high temeperature. Although this theory exists way back but we though of presenting it the results and hence may be this might help the researchers.

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