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# High Temperature Analysis of Si, SOI & SiC Piezoresistive Pressure Sensors

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***Abstract*— The paper discusses the high temperature performance of Silicon, Silicon on Insulator and Silicon Carbide based piezoresistive pressure sensors over the temperature range of 0 to 1000$^0$C. Junction leakage current is considered as one of the important parameters in this study and all the three sensors are analyzed for the junction leakage current. Simulation study reveals that the SiC based sensor has least temperature sensitivity compared to the other two sensors. In the design of SOI and SiC sensors the insulation layer is used between piezoresistors and the substrate. Junction leakage current is very small in case of SiC sensor. SiC sensor can be appropriate design for high temperature applications as SiC piezoresistors are very less sensitive to temperature.**

***Keywords*— SOI, SiC, piezoresistive pressure sensors. high tempearature, junction leakage current.***

## I. INTRODUCTION

MEMS is defined as the combination of electrical and mechanical components. The advancement in MEMS technology is because of its features such as small in size, low cost, batch fabrication and consumes low power. MEMS pressure sensors are broadly used in many applications. These pressure sensors are characterized based on sensing mechanism. Absolute, gauge and differential pressure sensor is three main MEMS pressure sensor [1]. Piezoresistive pressure sensor is categorized under differential pressure sensor. Silicon based piezoresistive pressure sensor are widely used in commercial and industrial applications. But recently emphasis is given on piezoresistive pressure sensor which is used in harsh environment where the temperature goes up to 300$^0$C [2]. Piezoresistive Pressure Sensors (pzr) are frequently used in chemical processing, aerospace, and automobile for pressure measurements. Piezoresistive materials are very much sensitive to the effect of temperature. As temperature changes the resistivity of the pzr material also changes [3]. A four piezoresistors connected in Wheatstone bridge configuration on a top of single crystalline Silicon substrate develops a residual stress. Such types of sensor have zero offset error which keeps on increasing as temperature increases [4]. A p-type piezoresistors on n-type substrate forms a junction. A leakage current is observed at this junction and it increases with respective to increase in the temperature. The leakage current affects the performance of the sensor. The temperature Coefficient of Resistivity (TCR) is a vital parameter in piezoresistive pressure sensor and it is always positive in single diffused crystal resistor. The sensitivity of the sensor is affected by TCR of piezoresistors which leads to Temperature Coefficient Sensitivity (TCS). The TCS gets negative as TCR increases [5]. By careful selecting the materials and tailor-made fabrication process we can avoid residual stress. By using an extra resistor on the diaphragm and use of double wheat stone bridge the temperature effect and zero pressure offset can be reduced [6-9]. Poly Silicon material can withstand at high temperature but piezoresistivity effect over the oxide layer is small [5]. [10] describes about Silicon on Insulator and its advantage over bulk silicon. SOI can provide stable operation at high temperature exceeds 125◦ C. It consists of buried oxide layer which can be used as insulating layer between the substrate and the piezoresistors [11-15]. The effect of leakage current can be reduced by using oxide layer [19].

## II. DESIGN AND SIMULATION OF SI, SOI AND SIC

The pzr sensor consists of four piezoresistors which are connected using connector line in the form of Wheatstone bridge configuration. R1, R2, R3 and R4 are the piezoresistors which are placed on the diaphragm as shown in fig 2.1. Here the diaphragm is used as sensing element. Piezoresistors are placed in high stress region.

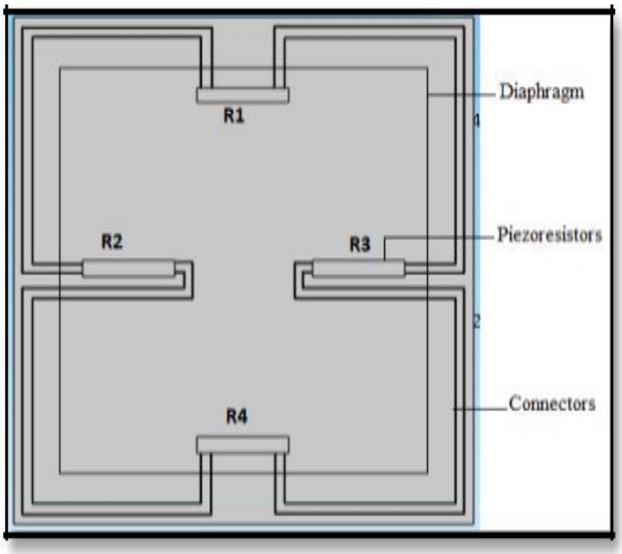


Fig 2.1 Proposed model of PZR sensor.

The dimension of the diaphragm for proposed model is length of 400µm, width of 400 µm and height of 10 µm. Dimension of Piezoresistors is length of 100 µm, width of 10 µm and thickness of 5 µm. The dimension of diaphragm and piezoresistors remains same for all three models. For SOI and

SiC model the oxide layer is used which has thickness of 2 µm.

TABLE 2.1. DIMENSIONS FOR ALL THE THREE 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 | 2 µm |
| Piezoresistors | p-type | 140µm | 10µm | 5µm |

Table 2.1 shows the dimensions for all three models [17]-[19]. But in SiC based model, we use SiC material for piezoresistors and rest of the things remains same.

TABLE 2.2 MATERIAL PROPERTIES OF ALL THREE 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 |

A pressure is applied on the diaphragm it starts to deform and displacement can be calculated using equation 1.

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

Where, P is applied pressure, a is side length of the diaphragm
E is Young's modulus of silicon, h is Thickness of the diaphragm, v is poison's ratio of silicon. The output voltage depends on input voltage and pressure applied to the device. It can be measured by using equation 2.

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

Where, $\pi_t$ = Piezoresistive coefficient for inverse position. The temperature sensitivity of piezoresistive pressure sensor is defined as the ratio of output voltage to the change in the temperature.

$$S = \frac{\Delta V}{\Delta T}\frac{1}{Vin} \qquad (3)$$

Where, S is Sensitivity of the pressure, ΔVis change in output voltage, ΔP is change in applied pressure and Vin is input Voltage to the pressure. The reverse leakage current is given by using equation (4)

$$I_s = qA(\frac{D_n n_{po}}{Wp} + \frac{D_p p_{no}}{Wn}) \qquad (4)$$

Where, A is cross sectional area of diaphragm, q is charge, $D_n$ and $D_p$ are diffusion coefficients of minority carriers, $W_p$ and $W_n$ are width of p-type and n-type Silicon, $n_{po}$ and $p_{no}$ are equilibrium concentration of minority carriers. Fig 2.2 Shows meshing of proposed model, user-controlled mesh is used to perform meshing.

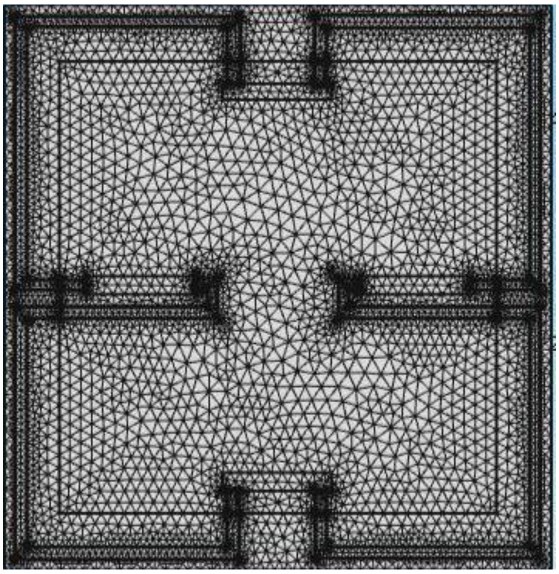

Fig 2.2 Sensor model after Meshing.

## III. RESULTS AND DICUSSION

In this segment the simulation results of Si, SOI and SiC models is discussed. Output parameter such as displacement, output voltage and leakage current are discussed. Pressure ranging from 0 kPa to 1000 kPa is applied to all three models.

### 3. 1 Displacement and output voltage analysis

Fig 3.1, Fig 3.2 and Fig 3.3 shows displacement of all the models. From the observation displacement of Si based pzr sensor is more as compared to SOI and SiC based pzr sensor.

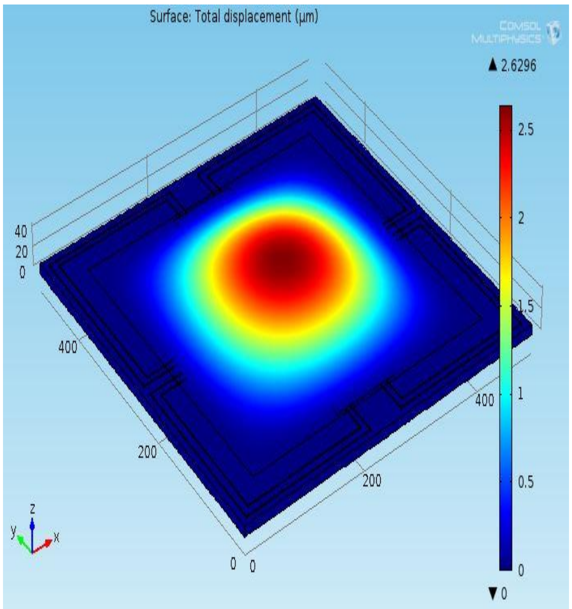


Fig 3.1 Deformation of Si based pzr sensor.

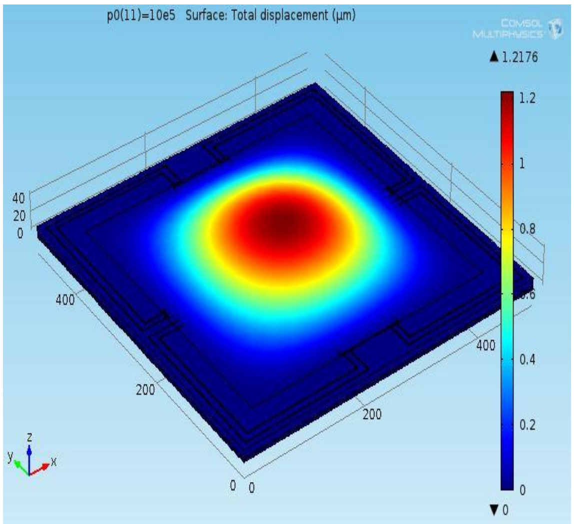


Fig 3.2 Deformation of SOI based pzr sensor.

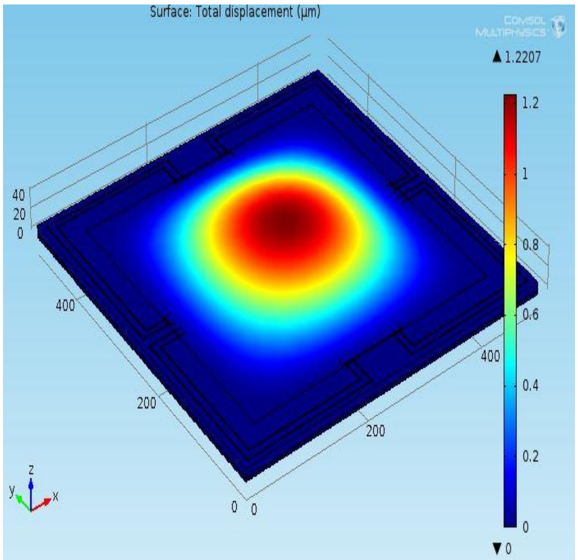


Fig 3.3 Deformation of SiC based pzr sensor.

The results for the output potential for both the sensors are presented in Table 3.1, 3.2 & Table 3.3. The same is plotted in Fig. 3.4.

Table 3.1 Simulated displacement and output voltage of Si based PZR sensor

| Applied Pressure (KPa) | Electric Potential(mV) |
|---|---|
| 0 | 374 |
| 100 | 414.53 |
| 200 | 454.59 |
| 300 | 494.19 |
| 400 | 533.31 |
| 500 | 572.01 |
| 600 | 610.26 |
| 700 | 648.09 |
| 800 | 685.5 |
| 900 | 722.51 |
| 1000 | 759.12 |

Table 3.2 Simulated displacement and output voltage of SOI based PZR sensor.

| Applied Pressure (KPa) | Electric Potential(mV) |
|---|---|
| 0 | 374.08 |
| 100 | 397.79 |
| 200 | 421.34 |
| 300 | 444.71 |
| 400 | 467.94 |
| 500 | 490.99 |
| 600 | 513.88 |
| 700 | 536.62 |
| 800 | 559.2 |
| 900 | 581.64 |
| 1000 | 603.91 |

Table 3.1 Simulated displacement and output voltage of Si based PZR sensor

| Applied Pressure (KPa) | Electric Potential(mV) |
|---|---|
| 0 | 2354.88 |
| 100 | 2376.50 |
| 200 | 2398.00 |
| 300 | 2419.37 |
| 400 | 2440.64 |
| 500 | 2461.78 |
| 600 | 2482.80 |
| 700 | 2503.71 |
| 800 | 2524.50 |
| 900 | 2545.19 |
| 1000 | 2565.77 |

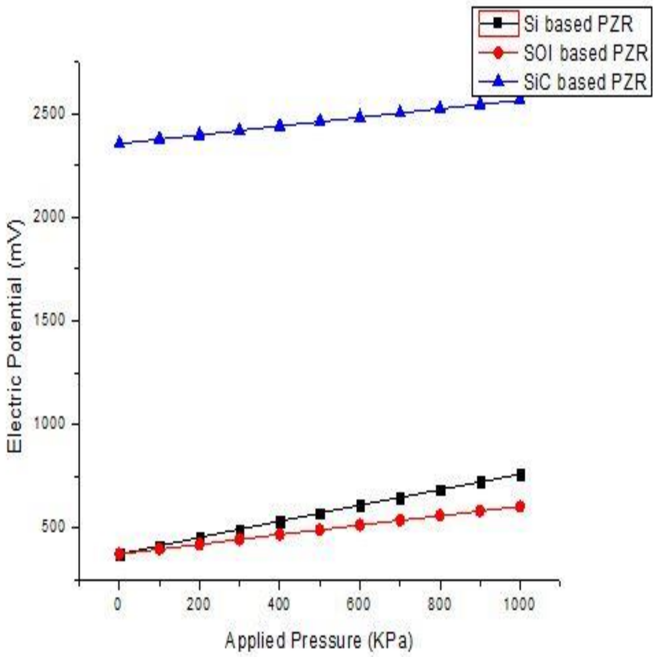


Fig 3.4 Applied Pressure v/s Electric Potential

Figure 3.5. shows Temperature versus Leakage current graph. Leakage current values 33.655μA to 96.95μA for SOI based Piezoresistive Pressure Sensor and 33.66μA to 96.96 μA for

SiC based Piezoresistive Pressure Sensor and also for 39.077µA to 110.55 µA Si based Piezoresistive Pressure Sensor when temperature ranges from 0◦C to 300◦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. And hence SiC based sensor shows very less junction leakage current & therefore less temperature sensitivity.

Table 3.4 Simulated Leakage Current values of SOI, SiC and Si based PZR sensor

| Temperature (In degrees Celsius) | SOI based pzr Leakage Current (µA) | SiC based pzr Leakage Current (µA) | Si based pzr Leakage Current (µA) |
|---|---|---|---|
| 0 | 33.65 | 33.66 | 39.07 |
| 100 | 42.96 | 42.97 | 51.30 |
| 200 | 59.44 | 59.45 | 75.06 |
| 300 | 96.95 | 96.96 | 110.05 |

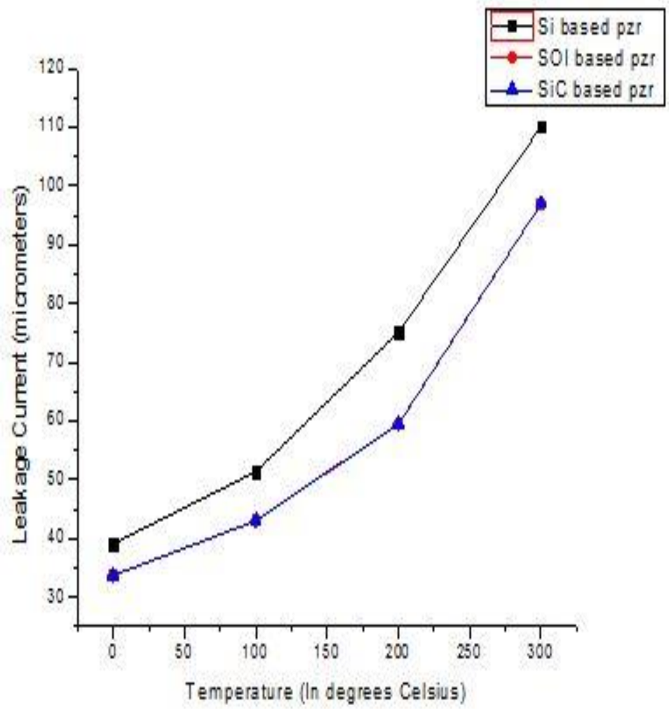


Fig 3.5 Temperature V/S Leakage Current

Table3.7 . Simulated values of electric potential for Silicon, SOI and SiC Based PZR Sensors

| Temperature (In degrees Celsius) | Si based pzr Electric Potential (mV) | SOI based pzr Electric Potential (mV) | SiC based pzr Electric Potential (mV) |
|---|---|---|---|
| 0 | 759.52 | 604.43 | 2565.84 |
| 200 | 757.77 | 604.05 | 2566.15 |
| 400 | 751.33 | 594.20 | 2567.30 |
| 600 | 744.94 | 586.21 | 2568.46 |
| 800 | 738.39 | 578.03 | 2569.66 |
| 1000 | 731.4 | 569.27 | 2570.96 |

Fig 3.6. shows Temperature v/s Electric Potential. Electric potential values 759.52 mV to 731.40mV for Si based PZR sensor and electric potential values 604.43 mV to 569.27mV for SOI based PZR sensor and also electric potential values 2565.84 mV to 2570.96mV for SiC based PZR sensor When temperature ranges from 0◦C and 1000◦C for applied pressure of 1MPa. From the observation, as temperature increases the electric potential starts to decrease linearly. Table 3.7 shows electric potential values for different temperatures

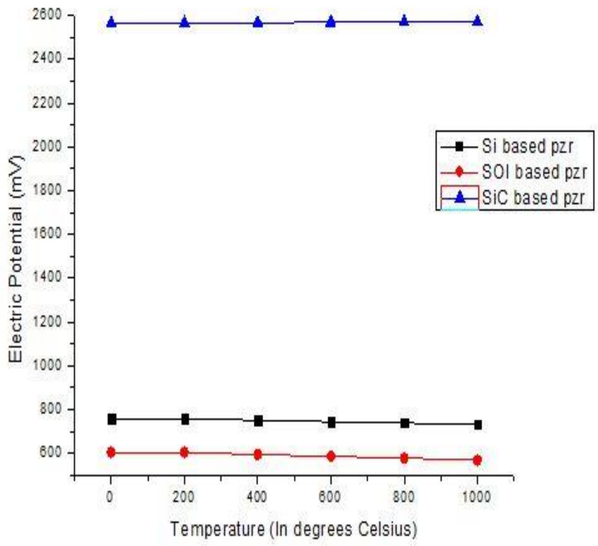


Fig 3.6. Temperature v/s Electric Potential.

Table3.7 . Temperature Sensitivity analysis of Silicon, SOI and SiC Based PZR Sensors.

| Pressure Sensors | Sensitivity (mV/◦K) |
|---|---|
| Silicon based PZR Sensor | |
| SOI based PZR Sensor | |
| SiC based PZR Sensor | |

## IV. CONCLUSION

In the paper we present the analysis of junction leakage currents for Si, SOI and SiC piezoresisitve pressure sensors. The leakge current analysis of all three sensors is done and the study reveals that the SiC based piezoresistive pressure sensor shows very less temperature sensitivity with littele junction leakage current. SiC piezoresistors used are less temperature sensistive and $SiO_2$ is used as an insulating layer between the resistors and the substrate, this further reduces the junction leakage current. Hence SiC is a formiddible replacement for the conventional piezoresistive pressrue sensors for high temperautre applications.

## REFERENCES

[1] R. S. Jakati, K. B. Balavalad and B. G. Sheeparamatti, "Comparative analysis of different micro-pressure sensors using comsol multiphysics," *2016 International Conference on Electrical, Electronics, Communication, Computer and Optimization Techniques (ICEECCOT)*, Mysuru, 2016, pp. 355-360. doi: 10.1109/ICEECCOT.2016.7955245.

[2] Guo S, eriksen H, Childress K, Fink a, Hoffman M (2009) High temperature smart-cut SOI pressure sensor. Sens actuators a 154:255–260

[3] Kanda Y, "A graphical representation of the piezoresistance coefficients in silicon", IEEE Transactions on electron Devices 29:64–70, 1982.

[4] M. J. Hu, B. C. Sang and H. L. Jong, "Design of Smart Piezoresistive Pressure Sensor, Science and Technology," *The 5th Korea-Russia International Symposium on Science and Technology*, Tomsk, 26 June-31 July 2001, pp. 202-205.

[5] K. N. Bhat, M. M. Nayak, "MEMS Pressure Sensor-An overview of challenges in 'Technology and Packaging", *Journal of ISSS*, Vol. 2, No. 1, March 2013, pp. 39-71.

[6] Chi-Chang Hsieh1, Chih-Ching Hung2, Yan-Huei Li3, "Investigation of a Pressure Sensor with Temperature Compensation Using Two Concentric Wheatstone-Bridge Circuits", *Modern Mechanical Engineering*, 2013, 3, 104-113 http://dx.doi.org/10.4236/mme.2013.32015 Published Online May 2013 (http://www.scirp.org/journal/mme).

[7] B.-N. Lee, K.-N. Kim, H.-D. Park, S.-M. Shin, Calibration and temperature compensation of silicon pressure sensors using ionimplanted trimming resistors, Sens. Actuators, A 72 (1999) 148–152.

[8] J. Gakkestad, P. Ohlckers, L. Halbo, Compensation of sensitivity shift in piezoresistive pressure sensors using linear voltage excitation, Sens. Actuators, A 49 (1995) 11–15.

[9] S.Maflin Shabya, M.S.Godwin Premib,Betty Martinc, "Enhancing the Performance of MEMS Piezoresistive Pressure Sensor using Germanium Nanowire", Proc. of 2nd International Conference on Nanomaterials and Technologies (CNT 2014), elviser 2014.

[10] S. Santosh Kumar and B. D. Pant, "Design principles and considerations for the 'ideal' silicon piezoresistive pressure sensor: a focused review", Microsyst Technol (2014) 20:1213–1247 DOI 10.1007/s00542-014-2215-7, 2014.

[11] Sivakumar K, Dasgupta N, Bhat KN, Natarajan K, "Sensitivity enhancement of polysilicon piezo-resistive pressure sensors with phosphorous diffused resistors", J Phys Conf Ser 34:216–221 2003.

[12] Kumar VV, Dasgupta A, Bhat KN (2006) Process optimization for monolithic integration of piezoresistive pressure sensor and MOSFET amplifier with SOI approach. J Phys Conf Ser 34:210–215.

[13] Yulong Z, Libo Z, Zhuangde J (2003) A novel high temperature pressure sensor on the basis of SOI layers. Sens Actuators A 108:108–111.

[14] Zhao LB, Zhao YL, Jiang ZD (2006) Design and fabrication of a piezoresistive pressure sensor for ultra high temperature environment. J Phys Conf Ser 48:178–183.

[15] Wang Q, Ding J, Wang W (2005) Fabrication and temperature coefficient compensation technology of low cost high temperature pressure sensor. Sens Actuators A 120:468–473.

[16] Kirankumar B. Balavalad and B. G. Sheeparamatti, "Design, Simulation & Analysis of SOI based Micro Piezoresistive Pressure Sensor for High Temperature Applications", Proc. of IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT-2018), IEEE XPLORE ISBN: 978-1-5386-2440-1, held at SVCE, Bengaluru May 18$^{th}$ – 19$^{th}$ 2018.

[17] Kirankumar B. Balavalad & B. G. Sheeparamatti, "Optimum Combination and Effect Analysis of Piezoresistor Dimensions in Micro Piezoresistive Pressure Sensor Using Design of Experiments and ANOVA: a Taguchi Approach" Sensors & Transducers, Vol. 211, Issue 4, April 2017, pp. 14-21.

[18] K. B. Balavalad and B. G. Sheeparamatti, "Design simulation and analysis of piezoresistive micro pressure sensor for pressure range of 0 to 1MPa," *2016 International Conference on Electrical, Electronics, Communication, Computer and Optimization Techniques (ICEECCOT)*, Mysuru, 2016, pp. 345-349. doi: 10.1109/ICEECCOT.2016.7955243.

[19] Kirankumar B. Balavalad, Vinayak. Lambi, 2019, Study and Analysis of Junction Leakage Current in Si & SOI based Micro Piezoresistive Pressure Sensor, *INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) RTESIT – 2019 (VOLUME 7 – ISSUE 08).*