A Review on Evolution, Current Trends and Future Scope of MEMS Piezoresistive Pressure Sensor

Kirankumar B. Balavalad,
Dept. of Electronics & Communication Engieenring,
Basaveshwar Engineering College,
Bagalkot, karnataka, India.
(Affiliated to VTU, Belagavi)

B. G. Sheeparmatti,
Dept. of Electronics & Communication Engieenring,
Basaveshwar Engineering College,
Bagalkot, karnataka, India.
(Affiliated to VTU, Belagavi)

***Abstract*— Piezoresistive pressure sensors are the first MEMS devices to be commercialized. They work on the principle of change in resistivity of materials due to applied pressure. Literature reports lot of work and development in this area of sensing mechanisms. This paper provides a review on evolution of these sensors right from thin metal film based technology to the semiconductor technology. The paper presents the current trends in the design and use of piezoresistive pressure sensor. The paper also presents the future scope form these sensors which, will be around the extensive use of materials like SOI, SiC, DLC, CNT and Silicon Nanowires.**

Keywords –MEMS, Piezoresistance, Pressure sensor, SOI, SiC, DLC, CNT.

I. INTRODUCTION

Pressure sensors are used for control and monitoring in thousands of everyday applications. Various types of pressure sensors do exist, which can be classified based on the sensing mechanism as, *Force collector* type of pressure sensors. *Capacitive* type uses a diaphragm and pressure cavity to create a variable capacitor to detect strain due to applied pressure, capacitance increases as pressure deforms the diaphragm. Common technologies use metal, ceramic, and silicon diaphragms. *Resonant* type uses the changes in resonant frequency in a sensing mechanism to measure stress, caused by applied pressure. *Thermal* type uses the changes in thermal conductivity of a gas due to density changes to measure pressure. *Ionization* type measures the flow of charged gas particles which varies due to density changes to measure pressure. Common examples are the Hot and Cold Cathode gauges. *Piezoresistive* strain gauge type uses the piezoresistive effect of bonded or formed strain gauges to detect strain due to applied pressure, resistance changes as pressure deforms the material. Common technology types are Silicon (single crystalline), Polysilicon, thin film, and bonded metal foil. Piezoresistive pressure sensors are one of the very-first products of MEMS technology. These sensors are widely used in biomedical applications, automotive industry and household appliances.

The piezoresistive pressure sensor have mainly been studied and commercialized because of high yield and wide dynamic range. In Piezoresistive pressure sensor, the piezoresistive effect is a change in the electrical resistivity of a semiconductor or metal when mechanical strain is applied. Piezoresistive pressure sensors provide high sensitivity enabling linear operation over wide range of pressure, suitable for high pressure applications. Piezoresistive pressure sensor technology is simple with highly standardized fabrication process, whereas capacitive and other techniques still face lack of process maturity in fabrication and nonlinear performance. The silicon based pressure sensor is one of the major applications of the piezoresistive sensor. The sensing material in a piezoresistive pressure sensor is formed on a silicon substrate, which bends with the applied pressure. A deformation occurs in diaphragm, leading to a change in the resistivity of the material. This change can be an increase or a decrease according to the orientation of the resistors. This paper aims at reviewing the evolution of piezoresistive pressure sensors for sensing applications starting from thin metal film to the complicated use of semiconducting materials like Silicon, Pollysilicon, SOI, SIC etc. The paper provides the current trends towards the design and development of piezoresistive pressure sensors taking current applications into consideration. Finally the paper tries to explore the future direction of piezoresistive pressure sensors.

II. EVOLUTION OF PIEZORESISTIVE PRESSURE SENSOR

The fundamental concept of piezoresistive effect is the change in receptivity of a material resulting from an applied stress. This effect in silicon material was first discovered by Smith in 1950's [1]. Smith proposed the change in conductivity under stress in bulk n-type material and designed an experiment to measure the longitudinal as well as transverse piezoresistance coefficients. In 1961 W.G. Pfann presented the shear piezoresistive effect, designed several types of semiconductor stress gauges to measure the longitudinal, transverse, shear stress and torque, and employed a Wheatstone bridge type gauge in mechanical signal measurement [2]. Lund and T. Finstad [3] in 1999 studied the temperature dependence of piezoresistance coefficient by four points bending experiment. In 1989 P.J. French and A.G.R. Evans [4] presented the piezoresistive effect in polysilicon and its applications to strain gauges. Piezoresistive pressure sensor design is widely studied at 1990's in MEMS and electronic packaging field by Jaeger et al [5, 6]. They employed piezoresistive sensor made on silicon chip to measure the stresses within electronic packaging devices.

This trend continued into the 1970s, when microsensor design began to move toward higher-volume, lower cost applications, specifically the automotive industry. Into the 1980s and the present, biomedical and automotive applications are some of the most widely reported in the literature. After 1980's the sensor need and requirements changed and there was a large demand for sensors which can perform better in harsh environments (mechanically and chemically aggressive). Soon after the sensors were begin to expose to harsh environments amongst which high temperature is one important parameter. In 1997 Y. Kanda applied MEMS process to fabricate piezoresistive pressure sensors on wafer for optimum design considerations. Recently finite element method (FEM) is widely adopted for stress prediction, thermal effect reduction, packaging design and reliability enhancement of piezoresistive sensor [7]. Temperature has its effect on the resistivity of piezoresisitors used in sensors. The performance of piezoresistive pressure sensors started deteriorating with increasing levels of temperature. Piezoresistive pressure sensor based on highly doped silicon and porous silicon was proposed by T. toriyama, Tanimoto, S.Sugiyama [8]. In 2008 the Shuwen Guo, Harald et all, proposed that the maximum operating temperature of a piezoresistive sensors can be raised when the silicon film is sufficiently thin. The minority-carrier exclusion effect in ultra thin film Smart-cut SOI enables resistance values to increase monotonically with temperature up to 600oC [9].

J. H. Kim, et all, proposed the use of the silicon nanowire in 2009, enabling the fabricated pressure sensor to have the enhanced sensitivity and the reduced sensor size [10]. In 2012 Haisheng San, et all, reveled that the performance of silicon piezoresistive pressure sensor suffers when they are operated in extremely harsh environment, such as vibration, shock and environment conditions with humidity, alkalescence or acidity, electrostatic particles and so on, its requirement in terms of reliability and stability is more rigorous than that of many advanced applications [11]

Hong Zhang, et all, in 2014 designed and fabricated a Si-Glass based MEMS piezoresistive pressure sensor for harsh environment applications. The sensor chips were fabricated using SOI wafer-glass anodic bonding technology, which enables a single boron-implemented piezoresistor to be on lower surface of silicon diaphragm and be vacuum-sealed in glass cavity [12]. Yangxi Zhang, at all, in 2014 reports a monolithic integration multifunctional MEMS sensor for acceleration and pressure measurement based on cavity SOI wafer. In 2015 G.D. Liu1, et all, proposed a SOI high temperature pressure sensor using a thermostable electrode of TiSi2/Ti/TiN/Pt/Au. Meanwhile piezoresistive ressure sensors using SIC (Silicon carbide) were designed and fabricated and literature shows few morks on SIC based MEMS pressure sensors. But the development of SIC films for sensors development suffers a lot with little process maturity. But efforts are being put by researchers towards development of SIC based piezoresistive pressure sensors.

III MEMS PIEZORESISTIVE PRESSURE SENSORS

Piezoresistive pressure sensor design consists of piezoresistive element resting on top/bottom of diaphragm. A contact is established with the electrodes, thus measuring the resistance of the electrode. The application of pressure on the sensor causes a deflection of the membrane and this causes a change in resistance of the electrode. The change in resistivity (R) can be measured as a change in voltage (V) or current (I) as given by Ohm's law: R = V/I [15, 16]. The best location to place the piezoresistors would be the region of maximum strain on the diaphragm. Piezoresistive sensors rely on the piezoresistive effect which occurs when the electrical resistance of a material changes in response to applied mechanical strain. In metals, this effect is realized when the change in geometry with applied mechanical strain results in a small increase or decrease in the resistance of the metal. The piezoresistive effect in semiconductors is primarily due to changes at the atomic level and is better than in metals. As stress is applied, the average effective mass of the carriers in the semiconductors for example, silicon either increases or decreases (depending on the direction of the stress, the crystallographic orientation, and the direction of current flow). This change alters the carrier mobility and hence its resistivity. When piezoresistors are placed in a Wheatstone bridge configuration and attached to a pressure-sensitive diaphragm, a change in resistance is converted to a voltage output which is proportional to the applied pressure.

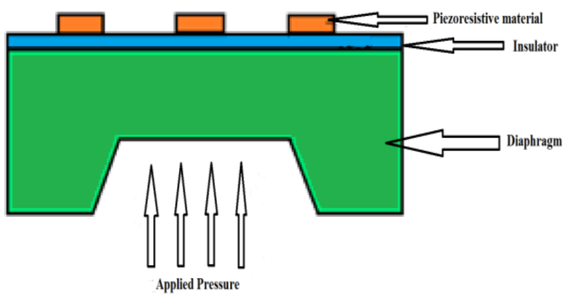

Fig.1Conventional pressure sensor

Fig. 1 illustrates a conventional piezoresistive pressure sensor model. Piezoresistors (orange colored blocks) are placed on top of the diaphragm (light blue colored) supported by substrate (green colored). the simulation set up of the piezoresistive pressure sensor with square diaphragm. The equations for maximum deflection and stress in a square diaphragm are given by [15] equation 1.

$$D = \frac{Eh^3}{12(1-v^2)}$$

The change of electric resistance in silicon piezoresistance gauge can thus be expressed as [16]

$$G = \frac{\Delta R}{R}\left(\frac{1}{\varepsilon}\right)$$

Piezoresistors are connected in Wheatrstone's bridge format to reduce temperature effects a bit. In a typical silicon pressure sensor made on (001) silicon wafer, membrane will be formed by anisotropic etching in KOH an etch stops on (111) planes. This etch creates the sides of the membrane oriented along <110> directions. The diaphragm is sealed from back side using anodic bonding in vacuum in order to measure the absolute value of pressure. Then stress/pressure applied can be measured by placing piezoresistors, often connected in a Wheatstone bridge, on the membrane. And the actual value of the pressure can be calculated from the output voltage of the bridge. Figure 2. Shows a simple diagram of four Piezoresistors connected in the form of Wheatstone's bridge.

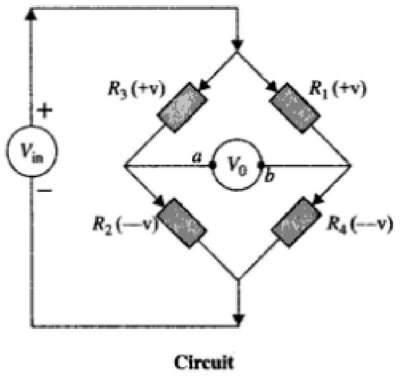

Fig.2 Piezoresistors connected in the form of Wheatstone's bridge

The output of a Wheatstone bridge can be given as [17]

$$V_{out} = \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) V_{in}$$

The materials used for diaphragm in order to provide mechanical support to sensor are typically silicon, aluminum, PMMA, PDMS, Polycrystalline silicon dioxide (Sio_2), Parylene C etc. The insulator is placed between diaphragm and piezoresistive elements, which acts as a substance in non-conductive state that reduce heat transfer. The different types of wafers used in design are silicon, SOI (silicon on insulator), Double SOI and SIC (Silicon Carbide). And different types interconnects used are metals such as Platinum, gold, copper). Both bulk and surface micromachining are employed for the fabrication of piezoresistive pressure sensor.

A. *Performance Parameters*

The sensitivity of a pressure sensor is defined as the relative change in the output voltage per unit applied pressure [18]

$$S = \frac{\Delta V_{OUT}}{\Delta P} \frac{1}{V_{in}} = \frac{\Delta R}{R} \frac{1}{R}$$

The deflection w_0 in the linear region of operation can be expressed as follows for a square diaphragm

$$\frac{w_0}{h} = \frac{Pa^4}{Eh^4 g_1}$$

The maximum stress σ_{max}, which occurs in the middle at the edge of the square diaphragm, can be expressed by the analytical expression for a square diaphragm as,

$$\sigma_{max} = p\left(\frac{a}{h}\right)^2$$

B. Simulation tools

Recently FEM/FEA is widely used for pre-analysis of the sensor for various parameters. The use of CAD tools can improve work efficiency, lower cost, shorten development cycle, and make the design more economic and products more competitive. Before actual fabrication it is very important to analyse the sensor for its performance. Using FEA/FEM tools thorough optimization will be done. Later after repeated analysis of the model it can be taken up for actual fabrication. The stress distribution of pressure sensors is simulated using tools like ANSYS, COVENTORWARE, COMSOL, MEMS+, SUGAR and MATLAB software's with the finite element method (FEM). These software's are very suitable for simulation and optimization of piezoresistive pressure sensors. Thickness and length-width ratio of the diaphragm and the arrangement of the piezoresistors on its surface are determined according to the simulation results.

C. Applications of piezoresistive pressure sensors

Piezoresistive pressure sensors are used in many applications such as household appliances, automotive application like Oil level, gas level, air pressure detection, barometric applications (weather forecasting) and Medical field (Non-invasive and invasive blood pressure monitors, Fetal heart rate monitors Inhalers and ventilators, Wound management, Patient monitoring systems, Spiro meter and respiratory therapy devices, Dialysis systems, Drug delivery systems.). The advantages of piezoresistive pressure are: Low-cost fabrication opportunity, mature processing technology, different pressure levels can be achieved according to the application, various sensitivities can be obtained easily and read-out circuitry can be either on-chip or discrete.

IV. CURRENT TRENDS IN MEMS PIEZORESISTIVE PRESSURE SENSORS

Due to advent of technology and requirements, many measurement and control applications require microsensors to be used in the harsh environments. Generally these environments include locations of high temperatures, intense vibrations, erosive flows or corrosive media. Application fields characterized by harsh environments include, for example, aerospace, micropropulsion, automotive, turbomachinery, oil well equipment, industrial process control, nuclear power, and communication. Now sensors are being exposed to such harsh environments amongst which high temperature is one important parameter. Materials like **SiC**, **SOI** and **DLC** are being extensively used for the design of sensors capable of achieving high temperature and pressure measurements. The current researchers are targeting high temperature ranges >800^{0}C. People are looking at materials which can operate fine at elevated temperatures with basic principles intact. Piezoresistive pressure sensors are now being developed using materials which have better physical, mechanical, chemical & electrical properties at high temperatures. This has evolved the development of sensors using materials like SiC, SOI & diamond, due to their excellent properties at high temperatures. Custom fabrication & packaging technologies are now being employed in the development of these sensors.

Temperature compensation along with the sensing element is being employed to help sensors to operate at high temperatures. One such attempt is the use of two concentric Wheatstone's bridge on the diaphragm [19]. Paper presents the design of silicon based temperature compensation were, eight piezoresistors are designed on the polycrystalline silicon membrane and constructed by two concentric Wheatstone-bridge circuits to form two sets of sensors. The sensor in the central circuit measures the pressure and temperature, while the outer one measures only the deflection caused by the working temperature. The other method employs the use of SiC (Silicon Carbide). SiC has high melting point of 2730°C and excellent thermal stability due to which SiC has become good material for many MEMS high-temperature pressure sensors. Silicon carbide also has many additional properties, such as low density, high strength, low thermal expansion, high thermal conductivity, high hardness, high elastic modulus, excellent thermal shock resistance, superior chemical inertness. Development of SiC is very difficult and fabrication is not yet matured [20]. In recent years, great progress in the growth of SiC bulk. Currently 6H-SiC, 4H-SiC and 3C-SiC wafers are commercially available. Paper [21], demonstrates 4H-SiC piezoresistive pressure sensor operating at 800^{0}C. SiC films are reported almost 15 times costlier than the conventional silicon. As an alternate, in recent years SOI has been extensively used in the fabrication of piezoresistive pressure sensors. SOI has been reported to operate normally till the maximum temperatures of 300^{0}C. Paper [22], demonstrates the novel high temperature pressure sensor, which is based on the SOI construction, replacing traditional pn junction insulation with SiO_2 insulation. Even researchers have focused their research towards the use of materials like DLC (Diamond Like Carbon) to be used in design of piezoresistive pressure sensor.

V. FUTURE OF MEMS PIEZORESISTIVE PRESSUR SENSORS

The future of MEMS piezoresistive pressure sensors will be focused around the extensive use of materials like SOI, SiC, DLC and Carbon Nanotubes. People are targeting the use of sensors in high temperatures hence researchers are trying new methods and designs using SOI and SiC which are found good for high temperature applications. The use of SOI and SiC has been briefly explained in the section above. Diamond is a superhard, wide bandgap, semiconductor material of high mechanical strength and thermal stability and therefore an ideal candidate for pressure sensors operating at elevated temperatures. Using these properties in a diamond-on-Si technology, a number of sensors and actuators have been attempted. However, their implementation lags behind that of silicon sensor technologies. Literature reports CVD diamond films deposition on Si-substrates, micromachined into structured membranes. New applications also need sensors to be a small as possible. Sensors now are being scalled down to nanoscale. In this regards people have demonstrated the use of carbon nanotube based piezoresistive pressure sensors, where the carbon nanotube is taken as piezoreisitor. The design and performance of a piezoresistive surface micromachined circular diaphragm based pressure sensor utilizing Single
walled Carbon nanotubes (SWNT) has been demonstrated in [23]. A piezoresistive nano structure is placed on the diaphragm. When the diaphragm deflects it results in change in the resistivity of the nano structure according to applied pressure. The paper shows, employing a nano structure results in increased sensitivity of the sensor.

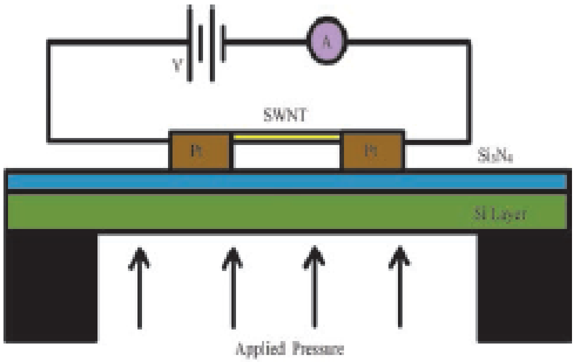

Figure 3. CNT based Piezoresistive Pressure Sensor model (reproduced from [23])

In the above figure, pressure sensor design consists of piezoresistive CNT element placed on top of Silicon/Si3N4 diaphragm. A contact is established with the SWNT utilizing platinum electrodes to measure resistance of the nanostructure. The application of pressure from back side of diaphragm causes deflection of diaphragm and this leads to change in resistance of the Carbon nanotube.

VI. CONCLUSION

The paper tries to present evolution of the piezoresistive pressure sensors. It all started from thin metal films and now onto semiconductors. The paper also presents briefly the design and mechanism of piezoresistive pressure sensor. Currently the research is focused onto designing sensors for harsh environments involving high temperature and high pressure. People are targeting the use of sensors at temperature more than 800^{0}C. And the future of MEMS piezoresistive pressure sensors rely around the use of materials like SOI, SiC, DLC, CNT and Silicon Nanowires.

REFERENCES

[1] C.S. Smith, Piezoresistance effect in Germanium and Silicon. Physical Review, Vol.94, 1954, pp.42-49.

[2] W.G. Pfann and R.N. Thurston, Semiconducting Stress Transducers Utilizing the Transverse and shear Piezoresistance Effects. Journal of Applied Physics, Vol.32, 1961, pp. 2008-2018.

[3] E. Lund and T. finstad, Measurement of the temperature dependency of the Piezoresistance coefficients in P-Type Silicon. advances in Electronic Packaging-ASME, EEP- Vol. 26-1, 1999, pp. 215-218.

[4] P.J. French and A.G.R. Evans, Piezoresistance in Polysilicon and It'sApplications to Strain Gauges. Solid-State Electronics, Vol.32, No.1, 1989, pp.1-10.

[5] R.C. Jaeger, J.C. Suhling, M.T. Carey, and R.W. Johnson, A Piezoresistive Sensor Chip for Measurement of Stress in Electronic Packaging. IEEE, 1993, pp.686-692.

[6] R.C. Jaeger, J.C. Suhling, A.T. Bradley, and J.Xu, Silicon Piezoresistive stress Sensors Using MOS and Bipolar Transistors. Advances in Electronic Packaging-ASME, EEP-Vol. 26-1, 1999 pp.219-225.

[7] Y. Kanda, Optimum desig Considerations for Silicon Piezoresistive Pressure Sensor, Sensor and Actuators. A62, 1997, pp.539-542.

[8] T. Toriyama, Y. Tanimoto, S. Sugiyama, "Single crystal silicon nano-wire piezoresistors for mechanical sensors", Journal of microelectromechanical systems, vol. 11, pp. 605-611, 2002.

[9] Shuwen Guo, Harald Eriksen, Kimiko Childress, Anita Fink, Mary Hoffman, "High temperature high accuracy piezoresistive pressure sensor based on smart-cut SOI", Advanced Sensors Technical Centre, Goodrich, 14300 Judicial Road, Burnsville, MN 55306, USA.

[10] J.H. Kim, K. T. Park, H.C. Kim, and K. Chun, "Fabrication of a piezoresistive pressure sensor for enhancing sensitivity using silico nanowire", SoEE, Seoul National University, Seoul, KOREA 2009.

[11] Haisheng San, Zijun Song, Xiang Wang, Yanli Zhao, Yuxi Y U, "A Novel Piezoresistive Pressure Sensor for harsh environment applications," Optics and Precision Engineering, Vol.20, No.3,2012.

[12] Hong Zhang, Huiming Xu, Yan Li, Zijun Song, Haisheng San, Yuxi YU, " A Si-Glass based Pressure Sensor with A Single piezoresistive element for Harsh Environment Application", School of Physical and Mechanical & Electrical Engineering, Xiamen University, Xiamen, China, Pen-Tung Sah Institute of Micro-Nano Science and technology, Xiamen University, Xiamen, China, Fujian Key Laboratory of Advanced Materials, Department of Materials Science and Engineering, College of Materials, Xiamen University, Xiamen, China.2014.

[13] Yangxi Zhang, Chenchen Yang, Fanrui Meng, Guandong Liu, Chengchen Gao, Yilong Hao, " A Monolithic Integration Multifunctional MEMS Sensor Based on Cavity SOI Wafer", Institute of Microelectronics, Peking University Beijing, 100871, China.2014.

[14] G.D. Liu1, W.P. Cui, H. Hu, F.S. Zhang, Y.X Zhang, C.C. Gao, and Y.L. Hao, " High Temperature Pressure Sensor Using a

[15] Thermostable Electrode", National Key Laboratory of Science and Technology on Micro/Nano Fabrication, Peking University, Beijing, 100871 China, State Key Laboratory of Transducer Technology, Chinese Academy of Sciences, Shanghai, 200050 China, Innovation Canter for MicroNanoelectronics and Integrated System, Beijing, 100871 China.2015.

[16] S. Timoshenko and S. Woinowsky-Krieger, "Theory of Plates and Shells," New York, McGraw-Hill., 1959.

[17] Carmen K. M. Fung, Maggie Q. H. Zhang, Rosa H. M Chan and Wen J.Li.A PMMA-Based Micropressure Sensor chip using Carbon Nanotubes as Sensing Elements. Centre for Micro and Nano Systems, The Chinese University of Hong Kong, Hong Kong SAR.0-7803-8732-5/05/$20.00 0 2005 EEE**.**

[18] S Santosh Kumar, Anuj Kumar Ojha, RamprasadNambisan.Design and Simulation of MEMS Silicon Piezoresistive Pressure Sensor for Barometric Applications. Semiconductor Piezoresistance for microsystems, Proc. IEEE.97 (2009) 513.

[19] K. N. Bhat and M. M. NayakMEMS Pressure Sensors An Overview of Challenges in Technology and Packaging. Institute Of Smart Structures And Systems (ISSS) J.ISSS Vol.2 No.1,pp. 39-71, March 2013.

[20] Chi-Chang Hsieh, Chih-Ching Hung, Yan-Huei Li, "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).

[21] Lung-Tai Chen, Jin-Sheng Chang, Chung-Yi Hsu, Wood-Hi Cheng, Fabrication and Performance of MEMS-Based Pressure Sensor Packages Using Patterned Ultra-Thick Photoresists, *Sensors*, 9, 2009, pp. 6200-6218

[22] Robert S. Okojie, Dorothy Lukco, Vu Nguyen and Ender Savrun, "4H-SiC Piezoresistive Pressure Sensor at 800^0C with Obsered Sensitivity Recovery", *IEEE Electron Device Letter*, Vol. 36, No. 2, Feb. 2015.

[23] Fu Xiansong, Yao Suying, Hou Shuzhi, Zhao Yiqiang Shengai, Zhang Weixin, "Simulation and Test of a Novel SOI High Temperature Pressure Sensor", 0-7803-8511-X/04, IEEE, 2004.

[24] S. Anand Selvin, S. Aravind Lovelin, N. Boovaraga Moorthy, Anju Gupta, M. Alagappan, Venkateswaran Ramalingam, "Design and Simulation of Carbon Nantube based Piezoresistive Pressure Sensor", Proc. Of COMSOL conference 2011.