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A Review on Development of MEMS Piezoresistive Pressure Sensor

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Abstract

This paper presents the comprehensive study of the Piezoresistive micro pressure sensor and different technique for optimization for enhancing its performance. Its different properties are of high sensitivity, high linear input/output relationship, and small size of in dimensions in micrometer are more demand in most of the industries. It used as a commercial sensing element in different sensors. The dimensions of piezo resistive micropressuresensors are highly compatible with the dimensions of biological, chemical species and other fields and hence make it more efficient and reliable to measure their properties. It has very interesting properties and also is a very good piezoresistors having high Piezoresistance co-efficient. In this paper a overview of the piezoresistive micropressure sensors development, properties, typical dimension, performance enhancement and applications are reviewed. The future of piezoresistive micropressure sensor is very bright and has wide range of impending applications due large operating pressure range.
Keywords –MEMS, Pressure sensor, Piezoresistance, SOI, SiC, DLC, CNT.

I.INTRODUCTION

Pressure measurement is essential necessity in day to day life applications, MEMS based pressure sensors are are most demanding in the field of pressure measurement due to their reliable, error free and exact measurements. Pressure is defined as the force applied per unit area. MEMS pressure sensor is a device converts physical quantity (such as Force, radiation, heat, pressure, magnetic field) into an electrical signal on exacting transduction mechanism. This electrical signal is usually used for recognition, measurement or control.

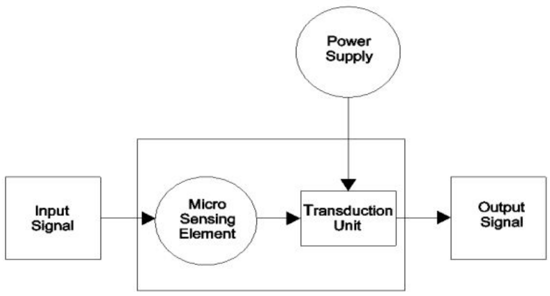

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Fig 1: Typical MEMS Pressure sensor model.

The Fig 1 shows Typical MEMS Pressure sensor model. When the outside pressure is applied on the sensor, the various transduction mechanisms convert the applied pressure into a understandable signal which is equivalent to the amount of pressure applied. The various transduction mechanisms used are capacitive, piezoelectric, piezoresistive. Each transduction mechanism works on a definite principle and produces an output which is suitable to measure the applied pressure. The output may be change in the capacitance, change in the potential/voltage, change in the frequency and change in resistance.

The phenomenon by which the electrical resistance of a material changes in response to mechanical stress is known as piezoresistivity. Piezoresistivity in semiconductor is widely applied in different sensors including pressure sensors, accelerometers, cantilever force sensors, and inertial sensors [1].

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 utilize piezoresistive effect as the detection mechanism. A Wheatstone bridge is built through electric connections with four piezoresistors to transform the resistance change into output voltage when pressure is applied on the membrane surface. Owing to their small scale, easy integration, direct signal transduction mechanism, etc. [2] piezoresistive pressure sensors have been most commonly used in most of the fields for pressure measurements. The MEMS pressure sensors have their wider application in the field of automotive industry, bio-medical and weather forecasting. Micro pressure sensors are also used to monitor and measure minute gas pressure in environments or engineering systems, e.g. automobile intake pressure to the engine. They are among the first MEMS devices ever developed and produced for “real world” applications.

II. EVOLUTION OF PIEZORESISTIVE PRESSURE

Amongst all the pressure sensors discussed above piezoresistive sensors (strain gauge) are widely used and acceptable by large**.** A strain gauge sensor is a passive transducer that converts mechanical displacement into the change in resistance. A strain gauge sensor is a thin wafer-like device that can be attached to a variety of materials to measure applied strain. Hence piezoresistive pressure sensors are well suitable for high level pressure sensing. They have lot of advantages when compared with the other transduction mechanisms. Piezoresistive sensors in silicon and germanium are among the earliest micro machined devices. According to Barlian, A et.al [3] the effect of stress on doped silicon and germanium has been known since the work of Smith at Bell Laboratories in 1954. And it is possible design an experiment to measure the longitudinal as well as transverse piezoresistance coefficients. In 1961 W.G. Pfann et.al [4] 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. In 1982, [5] Petersen et.al paper ''Silicon as a Mechanical Material'' reviewed several micro machined silicon piezoresistive devices and its different fabrication process and techniques. As the technology advanced in 1983 Sea-Chung Kim et al [6] studied the various mechanisms responsible for temperature sensitivity in silicon piezoresistive pressure sensors such as 1) temperature dependence of the piezoresistive coefficient, 2) gas expansion in the reference cavity (if present), 3) resistor tracking errors, 4) junction leakage current, 5) thermally-induced stress at the silicon-silicon dioxide inter- face, and 6) packaging effects. These are analysed by varying different dimensions of the structure. Invention in the polysilicon enhanced in the year 1989, P.J. French et.al [7] presented the piezoresistive effect in polysilicon and its applications to strain gauges. In 1990 Jaeger et al [8] worked further on piezoresistive sensor created on silicon chip to find out the stresses within electronic packaging devices and to overcome their effect. Piezoresistive sensors were the first commercial devices with three dimensional micromachining of silicon. Developments in the manufacture of semiconductors, transistor is resulted in improved methods of manufacturing piezoresistive sensors with low cost. with wide applications. Later sensors are required which can stand high temperature and perform better in harsh environments. Materials like **SiC**, **SOI** and DLCare being extensively used for the design of sensors capable at high temperature greater than 800^0C.In 1962, Kurtz et al [9] was the first to highlight the advantages of using higher doping levels for piezoresistors. The temperature dependence of sensitivity decreases with increasing surface concentration.

As the fabrication technology is improved in 1997 Y. Kanda et al [10] presented the optimum design to fabricate piezoresistive pressure sensors on wafer. Then inventions of the finite element method (FEM) and finite element analysis (FEA), virtual models helps engineers experiment with a particular structural design, usually with software work together to give engineers insight into the structural behaviour of particular designs, so they can locate weak points and improve them. With the help of these tools engineers can predict stress, thermal effect reduction, packaging design and reliability enhancement of piezoresistive sensor.

Ongoing advancements in IC fabrication, micromachining, and packaging technologies have given rise to the concept of fully integrated smart sensors in the form of monolithic silicon chips Piezoresistors, whose resistivity is dependent on strain. Moreover, minor processing variations give rise to piezoresistive tracking errors, which in turn alter the temperature characteristics for individual sensor. To overcome the variation of parameters with temperature, temperature compensation techniques have been reported. In the paper of M Akbar et al. [11] using laser trimming, extremer resistors, and clever use of material properties describes a fully integrated temperature compensation technique especially suited for batch fabrication of piezore sistive pressure sensors. which, if incorporated with a digital interface, produces a sensor operable from -40-130°C over a pressure range of one mega pascal. As the research on the sensitivity analysis and optimization of pressure sensor is continued researchers have found new materials are nothing but carbon nanotubes and silicon nanowire. These materials have high piezoresistive co-efficient and give better results compared with the typical bulk silicon. Advantage of carbon nanotubes over silicon are: High electrical and thermal conductivity, very high tensile strength, high flexible and elastic, high aspect ratios, good field emission [12].

Silicon nanowires (SiNW) of thickness 1-100 nm have very high piezoresistance effect compared to bulk silicon. *Izuan, A. Rashid*et al, [13] mentioned that sensitivity of the pressure sensor can be enhanced and we get optimized results by using Silicon nanowires (SiNW) of thickness 1-100 nm as piezoresistors. Hence SiNW is widely used sensing element in piezoresistive pressure sensor. Yangxi Zhang et al, in 2014 [14] designed a monolithic integration multifunctional MEMS sensor with beam block membrane for acceleration and low pressure measurement based on cavity SOI wafer. This sensor has small size and suited for dust environment. The other materials like silicon carbide (SiC) and silicon on sapphire can be used for the fabrication of high temperature pressure sensor. The SOI based high temperature pressure sensors are relatively low cost and good performance up to 600°C, which meets most of the industrial requirement. In 2015 G.D. Liu1, et al [15] proposed a SOI high temperature pressure sensor using a thermo stable electrode of TiSi2/Ti/TiN/Pt/Au. Meanwhile piezoresistive pressure sensors using SIC (Silicon carbide) were designed, fabricated and literature shows few marks on SIC based MEMS pressure sensors. But the disadvantage of SIC films for sensors is that its process is not much matured.

III. MEMS PIEZORESISTIVEPRESSURE SENSORS

Piezoresistance is defined as a change in electrical resistance of solids when subjected to pressure. The piezoresistive nature of silicon makes it feasible to

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covert the pressure into an electrical signal. Silicon material can be of p-type and n-type. Both p-type and n-type have different resistivity and piezoresistive co-efficient. The resistivity, longitudinal, transverse and shear piezoresistive coefficients of both n-type and p-type silicon are tabulated in Table 1.1

Table 1.1. Resistivity and coefficient values of p and n-type silicon

Type	Resistivity	Pi(11) Longitudinal piezoresistive coefficient	Pi(12) Transverse piezoresistive coefficient	Pi(44) Shear piezoresistive coefficient
Units	Ω-cm	10^-11 pa^-1	10^-11 pa^-1	10^-11 pa^-1
n-type	11.7	-102.2	53.4	-13.6
p-type	7.8	6.6	-1.1	138.1

For n-type, the longitudinal and transverse coefficients are more prominent compared with shear coefficient. For p-type longitudinal and transverse coefficients are negligible compared with shear coefficient. Piezoresistive pressure sensor can be designed using Wheatstone's bridge concept. The piezoresistors in the Wheatstone's bridge can be of p-type and diaphragm can be of n-type. Piezoresistive pressure sensor consists of a diaphragm on a silicon substrate. The four silicon piezoresistors are connected in Wheatstone's bridge form and are placed onto the diaphragm. The piezoresistors are usually placed at the center region of the diaphragm because when the pressure is applied onto the diaphragm, maximum deflection occurs at the center. With no pressure applied on the sensor, there is no deflection of the diaphragm and hence no stress is applied on the piezoresistors. Hence, the there is no change in the output voltage. When a pressure is applied on the sensor the diaphragm deflects and the stress is distributed among the piezoresistors which cause the change in the resistance of piezoresistors. When the resistance changes, there is a change in the output voltage of the Wheatstone's bridge which is equivalent to the applied pressure. Piezoresistors are connected in Wheatstone'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. The typical piezoresistive pressure sensor assembly is shown in Fig 2.

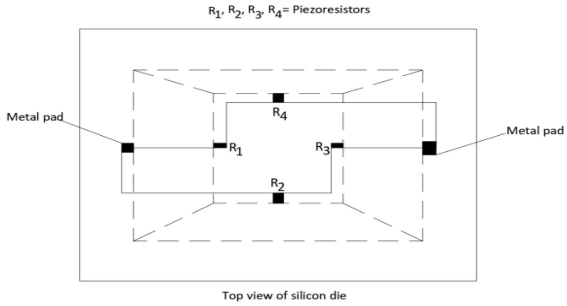

Fig 2. Typical piezoresistive pressure sensor assembly

The equations for maximum deflection and stress in a square diaphragm are given by

$W_{max} = 0.0151(1-\gamma^2)Pa^4/(Eh^2)$ (1.1)

$\sigma_{max}=0.308Pa^2/h^2$ (1.2)

Where ϒ – Poisson's ratio – 0.265 to 0.275

E- Young's modulus- 140 to 180 GPa

h- Thickness of diaphragm

P- applied pressure

a- Edge of square diaphragm.

R can be calculated by length l, cross sectional area A and resistivity (ρ) of the material as R =ρ l/A = ρl/wl (1 .3)

The output of Wheatstone bridge can be given as

Vo=Vs (R3 / (R3+R4) –R2/(R1+R2)) (1 .4)

Different models with different diaphragm shapes and sizes of piezoresistive pressure sensors have been developed using MEMS simulation tools and a comparison is made among the models in order to optimize the sensitivity of the sensor. In the paper of Nabiollah Abol Fathi et. al, [16] have developed pressure sensor models with different shapes(Square rectangular and Circular) of diaphragm using ABAQUS simulator. They concluded the rate of change in deflection is more in Circular diaphragm. The rate of change in stress is observed more in rectangular shaped diaphragm. The

circular shaped diaphragm with rectangular holes gives more sensitivity.
In another paper by Yozo Kanda et al. [17] developed a piezoresistive pressure sensor to improve sensitivity by considering different shapes of diaphragms with different arrangement of wheatstone bridge. Square diaphragm with double Wheatstone bridge and Circular diaphragm with single Wheatstone bridge are designed and simulated. The snapshot of the designed model is shown in Fig. 3.

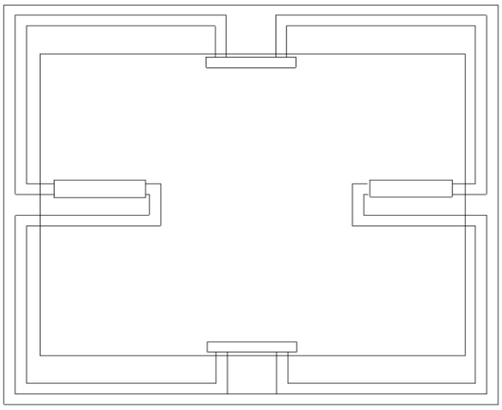

Fig.3. Snapshot of pressure sensor model

Ever going research on PZR to improve sensitivity and optimization, researchers have found new materials which can give better sensitivity and better results compared with typical piezoresistors. The materials used for diaphragm in order to provide mechanical support to sensor are typically silicon, aluminum, PMMA, PDMS, Polycrystalline silicon dioxide (Sio2), Parylene C etc. The insulator is placed between diaphragm and piezoresistive elements, which acts as a substance in nonconductive 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.
The new materials like carbon nanotubes and silicon nanowire acts as a piezoresistive sensors. These materials have high piezoresistive co-efficient compared with the typical bulk silicon and improved sensitivity and deflection.

IV.PERFORMANCE PARAMETERS

Piezoresistivity stress,strain, gauge factor, deflection, piezoresistors coefficient, sensitivity,resistance change, etc.are some parameters which measure the performance of piezoresistive sensors. The resistance change for a piezoresistor can be derived as the function of longitudinal and transverse stress as

$$\Delta R/R = \pi_l \boldsymbol{\sigma_l} + \pi_t \boldsymbol{\sigma_t} \qquad \textbf{(2 .1)}$$

Where, π_l and π_t are longitudinal and transverse piezoresristor coefficient. $\boldsymbol{\sigma_l}$ and $\boldsymbol{\sigma_t}$ are longitudinal and transverse stress.

Considering longitudinal stress, The gauge factor(GF) a common measure of the sensitivity of the sensor is defined as

$$GF= \Delta R/R/ \varepsilon = \pi_l \boldsymbol{\sigma_l} / (\boldsymbol{\sigma_l} /E) = \pi_l E \quad (2.2)$$

Where ϵ is the strain, E is the Young's modulus of the silicon. The deflection is given by

$$\boldsymbol{\delta} = (12aL-16a^2)aF/(4Et^3w) \qquad (2.3)$$

Where F is force, a is inner separation, w is width, t is thickness of the silicon beam, L is length of the beam. The maximum stress max σ, which occurs in the middle at the edge of the square diaphragm, can be expressed by the analytical expression for a square diaphragm as,

$$\boldsymbol{\sigma}max =P[a/h]^{2} \qquad (2 4)$$

V. SIMULATION TOOLS

There are different tools like FEA and FEM are widely used for optimization of sensors parameters. The use of CAD tools can model designs, devices, and processes in all fields of engineering, manufacturing, and scientific research. Repeated analysis of the model helps in work efficiency, lower cost, shorten development cycle, and make the design more economic and products more competitive. The stress distribution, temperature effect and reliability of pressure sensors is simulated using tools like ANSYS, VENTORWARE, COMSOL, MEMS+,SUGAR and MATLAB software with the finite element method (FEM). These software are very suitable for simulation and optimization of piezoresistive pressure sensors. Different dimensions of the diaphragm and organization of the piezoresistors on its surface are determined according to the simulation results.

VI. APPLICATIONS OF PIEZORESISTIVE PRESSURE SENSORS

The MEMS piezoresistive pressure sensors market is enhancing year after year. Over that time the largest technology driver for piezoresistive pressure sensor changed from automotive applications to consumer electronics. Beyond that, MEMS piezoresistive pressure sensors become the heart of whole classes of new devices like fitness trackers, smart watches, virtual reality glasses and smart sensor nodes for the Internet of Things. Silicon chips along with well special mixed signal circuitry, low power data processing, smart algorithms and connectivity to transform raw signals into meaningful information.

Multi-sensor applications & modules are playing an increasingly important role. In automotive industry these sensors are useful in Engine Management in Barometric Air Pressure (BAP), Diesel particulate filter and Mass flow sensor. In Vehicle Dynamics Control Engine Management, Diesel particulate filter Mass flow sensor vehicle, Dynamics Control Yaw rate sensor, High pressure sensor, In Safety Systems rollover sensor, Occupant weight sensor, Bolt Pedestrian Contact Sensor (PCS) Upfront Sensor (UFS) and Peripheral Pressure Sensor (PPS) and in 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.

VII. CURRENT TRENDS IN MEMS PIEZORESISTIVE PRESSURE SENSORS

As the advancement in technology PZR are developed which can operate in different environment with high sensitivity. In recent years SOI has been extensively used in the fabrication of piezoresistive pressure sensors. In Paper of Tsung-Lin Chou et. al [18], Piezoresistive pressure sensors based on SMART CUT SOI wafer have been developed, that the resistance value of a heavily doped thin film (~0.34 μm) resistor increases monotonically with temperature up to 600 to 3000°C. Further the maximum operating temperature range based on doping effects and minority-carrier exclusion effects.
To reduce the offset and temperature drift in silicon PZR there is one such attempt in paper by Y.T. Lee et. al [19] to arrange piezoresistors in double Wheatstone bridge. The offset voltage of the pressure sensor by the residual stress decreases with an increase in temperature. The offset of the inside bridge is larger than that of the outside bridge. However, its temperature variation in the outside bridge is larger than that of the inside bridge.
A novel high temperature pressure sensor is designed by the authors Fu Xiansong et al. paper [20] it replaces p n insulation with SiO insulation. The dielectric isolation develops low leakage current at high temperature. So, the sensors could be used in a high temperature environment.
The use of materials like DLC (Diamond Like Carbon) to be used in design of piezoresistive pressure sensor is also in demand due to its high values of Young's modulus, hardness, tensile strength and high thermal conductivity.
Due to advent of technology and requirements, much temperature compensation along with the sensing element is being employed to help sensors to operate at high temperature. One such attempt is the use of two concentric Wheatstone's bridge on the diaphragm. In one of the paper of *Chi-Chang Hsieh* et.al [21] 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 excellent thermal shock resistance and superior chemical inertness. Development of SiC is very difficult and fabrication is not yet matured. In the paper by Robert S. Okojie. et alb[22] explained great progress in the growth of SiC bulk. Currently 6H-SiC, 4H-SiC and 3C-SiC wafers are commercially available. But these SiC films are reported almost 15 times costlier than the conventional silicon.

VIII. FUTURE OF MEMS PIEZORESISTIVE PRESSUR SENSORS

The emerging approach for both chemical and biological MEMS sensors is based on carbon nanotube (CNT) and graphene-based technology. In the paper K. N. Bhat et.al [23] it is explained about importance of carbon nanotube . It is essentially concerned with materials, devices and systems to accomplish structures and components which exhibit novel and significantly improved physical, chemical and biological properties,. In this regards the design and performance of a piezoresistive surface micromachined circular diaphragm based pressure sensor utilizing single walled carbon nanotubes (SWNT).People are targeting the use of sensors in high temperatures and harsh environment hence researchers are trying new methods structures and designs using SOI and SiC which are found good for high temperature applications. Silicon carbide (SiC) sensors are high demand in for operation at temperatures in excess of 500°C and for operation in automotive applications as well as for corrosive fluids. Another material like diamond is a super hard, wide band gap semiconductor material of high mechanical strength and thermal stability and therefore operated at elevated temperatures.

IX. CONCLUSION

In this paper effort is made to presents the detailed study of the piezoresistive micropressure sensor. Different Materials used for piezoresistors, diaphragm and other structures are discussed. Design and working condition of piezoresistors in different environment are explained briefly. Based on characteristics and features of materials like silicon SOI,SiC,DLC, CNT are selected for respective application.

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