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MEMS Piezoresistive Pressure Sensor: A Survey

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ABSTRACT

Piezoresistive pressure sensors are one of the very first products of MEMS technology, and are used in various fields like automotive industries, aerospace, biomedical applications, and household appliances. Amongst various transduction principles of pressure sensor piezoresistive transduction mechanism is widely used. Over a decade therehas been tremendous improvement in the development of the design of piezoresistive pressure sensor starting with the invention of piezoresistance in the silicon to the recent piezoresistive pressure sensor materials. Because of its high sensitivity, high gauge factor, independent to the temperature, linear operation over a wide range of pressure, and many more advantages. This paper provides survey of piezoresistive pressure sensor including their pressure sensing mechanism, evolution, materials, design considerations, performance parameter that to be considered and the fabrication process used

Keywords-MEMS, Pressure sensor, Piezoresistor, Silicon

I. INTRODUCTION

In conjunction with temperature, pressure is one of the major physical quantities in our environment. A pressure sensor often acts as a transducer; it produces a signal as a function of the pressure imposed. MEMS pressure sensors are covering foremost part of the sensor market in contemporary years and are fast developing with brand new capabilities. Pressure sensors are used in many applications like aerodynamics, biophysics, automobile, safeguards and many more domestic applications. Various types of pressure sensors can be categorized based on the sensing mechanisms they are. 1.1 Absolute pressure sensor measures static, dynamic or whole pressure with reference to a vacuum. 1.2 Gauge pressure sensor calculates the pressure relative to atmospheric pressure. When it shows zero, then the pressure it is measuring is same as the ambient pressure. 1.3 Relative pressure sensor measures static, dynamic or total pressure with regards to the ambient pressure. 1.4 Optical pressure sensor techniques include the use of anphysical change in the optical fiber to detect the strain due to an applied pressure. This technology is employed in many challenging applications where the measurement may be highly remote, under high temperature, or may benefit from applied sciences inherently immune to electromagnetic interference. 1.5 Differential pressure sensor measures the difference between two pressures, one connected with each side of the sensor. Differential pressure sensors are used to measure many properties like pressure drops through oil filters or air filters, fluid levels or flow rates. 1.6 Piezoresistive pressure sensor uses the piezoresistive effect of bonded strain gauges to detect the strain due to an applied pressure, resistance increasing as pressure deforms the material. Common methods that uses piezoresistive technologies are Silicon (Mono crystalline), Polysilicon Thin Film, Bonded Metal Foil. 1.7 Capacitive pressure sensor uses a diaphragm and pressure cavity to create a variable capacitor to detect strain due to applied pressure, capacitance decreasing as pressure deforms the diaphragm. 1.8Resonant pressure sensor uses the changes in resonant frequency in a sensing mechanism to measure stress, or changes in gas density, caused by applied pressure.

Many MEMS instruments were manufactured and commercialized from several years and have reached consumer. The present pressure sensors going through many challenges that has to be used in the application like high pressure. Temperature is a main factor in the efficiency of MEMS pressure sensor, were these have to be used in many applications like aerospace utility and harsh environment. Consequently, for this kind of environment special sensing devices are requiring to adapt a high temperature and high pressure environment. Among all the various type of MEMS pressure sensor piezoresistive pressure sensors are widely used, because these sensors provides a high sensitivity and it allows a linear operation over a wide range of pressure. Piezoresistive pressure sensors are one of the very first products of MEMs technology. Those products are broadly used in biomedical applications, automotive enterprises and household appliances. The piezoresistive pressure sensor have mainly been studied and commercialized because of their high yield and wide dynamic range. A silicon based pressure sensor is one of the major applications of the piezoresistive sensor. Recently MEMS situated technologies includes silicon (Si), silicon on insulator (SOI), silicon on sapphire (SOS), silicon carbide (SiC), steel, carbon nanotubes (CNT) and diamond had been observed to be in a position to furnish the critical ruggedness to be capable to adapt and provide the better performance in harsh environment. This paper focus on the survey of MEMS based piezoresistive pressure sensor, current trends involved in development of piezoresistive pressure sensor and their outlook. Section II explains about the evolutions of piezoresistive pressure sensor. Principle and sensing mechanism of piezoresistive pressure sensor is explained in section III. Section IV is about the materials that are used in the design of diaphragm and their properties. Section V and VI discuss about the performance parameter and the design consideration of the piezoresistive pressure sensor. The fabrication of the piezoresistive pressure sensor is discussed in section VII.

II. EVALUTION OF PIEZORESISTIVE PRESSURE SENSOR

Ever since the discovery of Piezoresistance in silicon by C.S.Smith in1954 [1] silicon based micro pressure sensors have been extensively studied over the past three decades. Pfann and Thurston [2] were among the first to realize a working of MEMS based pressure sensor designed using two longitudinal and two transverse diffused piezoresistors in the Whetstone's bridge for better sensitivity. Kanda [3] in his work has presented a model which enables the calculation of piezoresistive coefficients as a function of doping concentration and temperature. Enhancing the sensitivity has also been a main issue in the research of micro pressure sensors. Design modifications like employing a bossed diaphragm and multiple diaphragms [4, 5] and material modification by using phosphorous diffused polysilicon piezoresistors [6] polymer diaphragms and alternate piezoresistive materials [7-10] have also been studied. The other technology can be brought to solve the isolation problem of devices and substrates, but increases the fabrication cost greatly. The discovery of piezoresistive effect in polysilicon in the 1970s [11] facilitates its applications for sensing devices [12, 13]. As for polysilicon, the p-n junction isolation is avoided, so that the devices can work at higher temperatures. Moreover, polysilicon based devices have the advantages of low cost, facile processing and good thermal stability, compared to homogeneous silicon based devices. It can be seen that it is necessary to investigate the piezoresistive properties of polysilicon and built up the theoretical model. The experimental results reported by other researchers indicated that the GF of Polysilicon common films (PSCFs, film thickness $\geq$ 200 nm) reaches the maximum as the doping concentration is at the level of 1019 cm^3, and then decreases drastically as doping concentrations are increased further [14, 15-17]. Based on this phenomenon, the existing piezoresistive theories of Polysilicon were established during 1980s~1990s and used to predict the process steps for the optimization of device performance.

Later years carbon nanotubes have drawn much attention since their discovery in 1991 because of their unique electronic and mechanical properties. In 1991, multi-walled nanotubes were first discovered by Ijima by arc-discharge technique when he saw fine threads in a bit of shoot under electron microscope. The strands were very thin and long tubes of pure carbon. SWNTs were synthesized for the first time by Ijima and Ichihashi [18] and Bethune et al. [19] in 1993 using metal catalyst in arc-discharge method. Laser-ablation technique was used by Thess et al. [20] in 1996 to produce bundles of aligned SWNTs. For the first time, catalytic growth of MWNTs by CVD was proposed by Yacaman et al. [21]. Liu [22] and Dai [23] demonstrated that piezoresistive pressure sensors can be realized with CNTs. They grew SWNTs on suspended square polysilicon membranes. When uniform air pressure was applied on the membranes, a change in resistance in the SWNTs was observed. Moreover, the membrane was restored to its original condition when the gas was pumped out, indicating that the process is reversible. Dharap et al.[24] argued that the conventional sensors have disadvantage that they are discrete point, fixed directional, and are not embedded at the material level. To overcome these limitations, they developed a CNT film sensor for strain sensing on macro scale. The sensor was based on the principle that the electronic properties of CNTs change when subjected to strains. In recent years high temperature pressure sensor is one of the hot research topics in the industry. Because of the special environments they are used in, the requirements for the design and manufacture of the sensor are very strict. It is important to research high temperature pressure sensors for every walk of life [25, 26]. So Silicon carbide (SiC) has been recognized as an appropriatesemiconductor material for harsh environments such asspace applications and terrestrial applications in the aeronautical,automotive and petrochemical fields proposed Staufferet al; George et al. 2006 Many studies show thatSiC devices are capable of operating well in these applicationsthat involve high-temperature, high-radiation andcorrosive environment by Azevedo and Jones; WrightandHorsfall [27, 28] 2007.

Another material that can withstand the high temperature and high pressure is a SOI. We know that the temperature dependence of the piezoresistive effect in silicon is well documented in the literature. It is known how the piezoresistive coefficients change with the temperature. The temperature limit has been verified up to 175 °C for silicon sensors and up to 500 °C for silicon-on-insulator (SOI) technology [29] by Fraga et al. 2011. Later Haisheng San, Zijun Song, Xiang Wang, Yanlizhao, and Tuxi Y. U, proposed that the silicon piezoresistive pressure sensor is a mature technology in industry, but when the pressure sensors are operated in extremely harsh environment, such as vibration, shock and environment conditions with humidity, alkalescency or acidity, electrostatic particles and so on, its requirement in terms of reliability and stability is more rigorous than that of many advanced applications so for these application we have to choose a SOI rather than silicon [30].

III. PIEZORESISTIVE PRESSURE SENSING MECHANISM

Piezoresistive, capacitive, optical, resonance, acoustic transduction principle used in the contemporary work within the progress of the micro machined pressure sensor modelling, design and fabrication used to be reviewed in [31]. Among these pressure sensor transduction principle, piezoresistive and capacitive transduction mechanisms have been widely adopted in various fields. Many commercialized MEMS pressure sensor [32-36] uses a piezoresistive transduction mechanism in order to shows the pressure change in the resistance. Most researchers preferred piezoresistive technique, because the properties of silicon material have been well established and the facilities of current silicon foundry can be utilized for batch fabrication. And also piezoresistive pressure sensor has excessive high gauge factor but it has 0.27% per °C of temperature coefficient of Piezoresistivity (TCP). The design of piezoresistive pressure sensor consists of piezoresistive element placed on a top of the diaphragm. Placement of piezoresistive element on the square diaphragm is very important design consideration to achieve the required sensitivity. The optimal location to place the piezoresistive material would be in the region of high stress on the diaphragm. Then these resistors are connected in the form of Whetstone's bridge [1, 37]. The application of pressure beneath the sensor causes a deflection of the membrane and this causes a change in resistance of the piezoresistive elements. As a result, the calculation of stress distribution and deflection in accordance with the applied pressure becomes pivotal.

These forms of piezoresistive based transducers depend on the piezoresistive effect which occurs when the change in electrical resistance of a material in response to the mechanical strain is applied [38]. 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 silicon is primarily due to its atomic level. As stress is applied, the average effective mass of the silicon carrier will either increases or decreases (depending on the orientation of the crystallographic, direction of the stress, and the direction of the current flow). This type of change alters the silicon carrier mobility and hence it results in the change in its resistivity. When piezoresistive element are placed in the Wheatstone bridge configuration and it is attached to the pressure-sensitive diaphragm, a resistance change in the material is converted in to an output voltage which is proportional to the applied pressure as shown in the Fig.1.

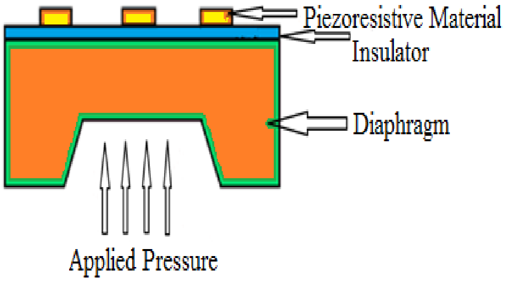

Fig.1. Conventional pressure sensor model

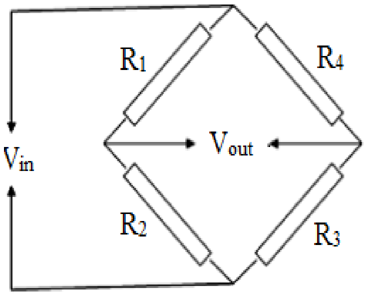

Fig.2. Wheatstone bridge circuit.

Fig.2. shows the Wheatstone bridge circuit, a Wheatstone bridge consists of a four piezoresistive material labeled as R_1, R_2, R_3 and R_4 respectively. The resistance [R] of a piezoresistive material is given by

$$\mathbf{R} = \rho \frac{L}{A} \qquad \mathbf{(1)}$$

Where ρ is the resistivity of a piezoresistor, L is the length of a piezoresistor; A is the area of a piezoresistor. 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. From equation (1), if length increases and area decreases, there will be incremental change in the resistance of a piezoresistors and effectively decreases the output voltage.

IV. MATERIALS OF PIEZORESISTIVE PRESSURE SENSOR

In the above discussion it is clear that depending on the application we have to use a different piezoresistive material for the model, like silicon (Si), silicon on insulator (SOI), silicon on sapphire (SOS), silicon carbide (SiC), steel, carbon nano tubes (CNT) and diamond. However the principle remains same as the piezoresistive mechanism of pressure sensing. The material used to design the diaphragm on which the piezoresistive materials are placed, plays on very important role in deciding the application of a pressure sensor. Table 1 and 2lists the properties of various diaphragm and piezoresistive material respectively.

Table 1 Properties of various diaphragm materials

Sl. No	Materials	Density	Young's Modulus	Poisson's ratio
1.	Silicon di oxide	2270	70	0.17
2.	Poly Silicon	2320	169	0.22
3.	Steel AISI 4340	7850	205	0.28
4.	Al_20_3	3970	393	0.27
5.	Si_3N_4	3310	317	0.23
6.	Germanium	5323	103	0.26
7.	Al	2700	70	0.25
8.	Cu	8960	120	0.34

Table 2 Properties of various piezoresistivematerials

Sl. No	Materials	Density	Young's Modulus	Poisson's ratio
1.	Single crystalline Si (n, p type)	2270	70	0.17
2.	Carbon Nanotubes	1600	1000	0.2
3.	Diamond	3.5	10.35	---
4.	SIC	3.21	476	0.19
5.	Silicon	2330	160	0.22
6.	SOS	3.97	250-400	0.29
7.	Polycrystalline Si	2330	160	0.23

In the piezoresistive pressure sensor output signal is from the Wheatstone bridge. The resistance of the bridge is distributed in four directions. The output signal V_{out} is $V_{in}\Delta R/R$. V_{out} is the output voltage (V), V_{in} is the input signal voltage (V), ΔR is the change in resistance (KΩ), and R is the initialvalue of the resistance (KΩ). The amount of change in voltage sensitivity of resistors is [39].

$$\Delta R/R = \pi_l \sigma_l + \pi_t \sigma_t \qquad (2)$$

Where $\sigma_l$is the longitudinal stress parallel to the current direction in the internal of resistance (N/m^2), $\sigma_t$is the transverse stress perpendicular to the current direction (N/m^2), π_l is the longitudinal piezoresistive coefficient of silicon (m^2/N), the same direction as the longitudinal stress, $\pi_t$is the transverse piezoresistive coefficient of silicon (m^2/N), the same direction as the transverse stress. Table 3 shows the piezoresistive coefficient for <100> silicon wafer.

Table 3 Piezoresistive coefficients of silicon

Sl. No	Wafer type	π_l	π_t	Orientation
1.	P-type	-31.6	-17.16	<110>
2.	N-type	71.8	-66.3	<110>

V. PERFORMANCE PARAMETERS

When the pressure is applied on the diaphragm, it tends to get deformed, having a maximum displacement at the centre of the diaphragm. The value of displacement decreases near the fixed ends of the diaphragm. The quantity of displacement is measured at the centre of the diaphragm [40] using the following equation

$$X = \frac{0.00126PL^4}{D} \qquad (3)$$

Where P is the Pressure applied on the diaphragm, L is the Length of the diaphragm, and D is the Bending rigidity of the diaphragm material and is given as

$$D = \frac{Et^3}{12(1-v^2)} \qquad (4)$$

Where E is the Young's Modulus of diaphragm material, t is the thickness of the diaphragm, and v is the Poisson's ratio of the diaphragm material. The amount of sheer stress experienced at the mid-point of the diaphragm [41] is given as

$$\square = \left(\frac{L}{t}\right)^2 \qquad (5)$$

It can be seen from (3) and (5) is that, increase in the pressure applied on the diaphragm, increases the sheer stress at the mid-point of the diaphragm, also increases the displacement or deformation of the diaphragm. The displacement of the diaphragm also depends on the dimensions of the diaphragm as well as the stiffness property (Young's modulus) of the diaphragm material. When the pressure is applied on the diaphragm with four blocks as piezoresistor, the stress induced in the diaphragm change the resistance of piezoresistor due to piezoresistive effect. The change in the resistance of the piezoresistor is denoted by ΔR. Due to the deformation of the diaphragm in the direction of pressure applied, it is said that the length of the piezoresistor increases which in turn increases the resistance of the piezoresistive material (using equation 1). Thus it can be concluded that, as the pressure increases, the resistance of the piezoresistor will also increases linearly.The next parameter is the output voltage across the Wheatstone bridge. The output voltage of the Wheatstone bridge depends on the input voltage applied to the bridge circuit and also the resistance values of all the four piezoresistive materials. Hence, as the resistance of the piezoresistive materials changes due to the applied pressure, the output voltage of the Wheatstone bridge also varies. The output voltage [V_{out}] across the Wheatstone bridge circuit is given by,

$$\mathbf{V_{out} = \left[\frac{R2R3 - R1R4}{(R1+R2)(R3+R4)}\right] V_{in}} \qquad \textbf{(6)}$$

Where V_{in} is the Input voltage applied to Wheatstone bridgefrom (6), when R2R3 = R1R4, V_{out}= 0. This means that the bridge is in the balanced condition and theoretically no pressure is applied onto the diaphragm. When there is no pressure on the diaphragm, the resistance values of all the piezoresistive elements will be theoretically identical, hence Vout = 0. But practically it may be difficult to fabricate the piezoresistive elements of equal resistances, due to which the output voltage may not be zero when no pressure is applied. The relation of electric field in the vicinity of surface of the diaphragm with applied stress is given by (7).

$$\mathbf{E = \square\ J + \square\ \square\ J} \qquad \textbf{(7)}$$

Where ρ is the resistivity of piezoresistors, J is the current in piezoresistors, and Δρ is the induced change in resistivity. This is given by the equation

$$\square\ \square = \square.\ \square$$

Where π is the piezoresistance tensor and γ is the shear stress given by (5).The performance of any model can be estimated based on the sensitivity of the sensor to the pressure applied and the gauge factor. For the system to be better, it should be highly sensitive. In other words, there should be large decrease in the output voltage and large increment in the resistance of piezoresistive element due to a small increase in the pressure applied to call a device as highly sensitive. Gauge factor is another parameter which determines the performance of the piezoresistive pressure sensor [42]. The Gauge factor of the pressure sensor is the change in resistance to the amount of volumetric strain acting on it. It is given by

$$\mathbf{G = \frac{\Delta R}{R\varepsilon}} \textbf{(8)}$$

Where ε is the Strain of the pressure sensor

The Gauge factor value should be large (in the range of 500 to 1000) to indicate the better performance of the pressure sensor.The sensitivity of the pressure sensor is defined as the relative change in the output voltage per unit of applied pressure [43]. The sensitivity of the piezoresistive pressure sensor is given by.

$$\mathbf{S = \frac{1}{V_{in}} \frac{\Delta V}{\Delta P}} \qquad \textbf{(9)}$$

Where S is the sensitivity of the pressure sensor, ΔV is the change in the output voltage, and ΔP is the change in the pressure applied. The output voltage of the pressure sensor without any pressure being applied is called an offset voltage. This is due to mainly two reasons. The first one is due to some residual stress on the membrane. And the second one, which is main reason, is variability in the four resistors. While the resistors are processed at the same time, there are some variations. The offset voltage can be compensated by connecting external resistors. It can be compensated using compensating resistors along with electronics.

VI. DESIGN CONSIDERATION

6.1. Fracture Stress:

Fracture stress is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for many design applications. The linear-elastic fracture stress of a material is determined from the stress intensity factor at which a thin crack in the material begins to grow. It is denote ($\sigma_{fracture}$)

6.2. Yield Strength:

A yield strength or yield point is the material property defined as the stress at which a material begins to deform plastically. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible.

6.3. Burst Pressure:

Another important design consideration of a piezoresistive pressure sensor is a burst pressure. We know that as the applied pressure on the diaphragm increases, the stress on the diaphragm increases correspondingly. As a result, when the maximum stress on any portion of the diaphragm exceeds the yield strength of the diaphragm material, the diaphragm will burst. While this burst pressure governs the maximum operating pressure of a pressure sensor, the linearity of operation determines the maximum pressure up to which the sensor can be used within the limits of the specified accuracy. The burst pressure is decided by a number of factors including diaphragm shape, thickness, lateral dimensions, ruptures stress of the material and diaphragm surface roughness and is given by [44].

$$P_b = \frac{3.4F_{Max}h^2}{A(1-\nu^2)} \qquad (10)$$

Where F_{Max} is theFacture stress, h is the Diaphragm thickness, $\nu$is the Poisson's ratio, A is the Diaphragm area.

6.4. Diaphragm dimension:

As the stress on the piezoresistors is due to the stress on the diaphragm, it is important to choose the thickness and size of the diaphragm carefully in order to obtain the best output characteristics from the sensor. Pressure sensors with thinner diaphragms give better sensitivity whereas thicker diaphragm gives better linearity. Usually, the diaphragm in a pressure sensor is modified as a square diaphragm with all the edges clamped. A diaphragm can be considered as a thin diaphragm, if the ratio of thickness to the length of diaphragm is less than 1/20, [44]. The small deflection theory for bending of thin plates assumes that the deflection of midpoint of surface of the diaphragm must be small compared to the thickness of the plate and the maximum deflection must be less than 1/5th of the thickness of the diaphragm [45].

6.5. Temperature Coefficient ofResistance(TCR):

The change in the resistance of the material per degree Celsius change of temperature is known as the temperature coefficient of resistance. A positive coefficient of the material means that its resistance increases with increases in the temperature (Pure metal typically have a positive temperature coefficient of resistance). A negative coefficient of the material means that its resistance decreases with an increases in the temperature (Semiconductor materials like carbon, silicon, germanium typically have a negative temperature coefficient of resistance). The equation for the TCR is given by,

$$R= R_{ref}[1+\alpha(T-T_{ref})] \qquad (11)$$

Where α is the temperature coefficient of resistance, R is the resistance of the material at temperature T, R_{ref} is the reference resistance, T is the temperature in degree Celsius, and T_{ref} is the reference temperature.

VII. FABRICATION METHODOLOGY

Many fabrication methods have been investigated to date. They all aim at a thin monocrystalline silicon film on top of an insulator with defect densities as low as in bulk material. The best compatibility with standard silicon processing techniques can be attained with sandwich structures. A typical fabrication of the piezoresistive pressure sensor is shown in Fig.3. It is made up of <100> crystal orientation of the silicon wafer and a membrane has been formed by an anisotropic etching using a KOH etch stop, in the <111> plane. Due to the nature of this etch; the sides of the membrane are oriented along <110> direction.

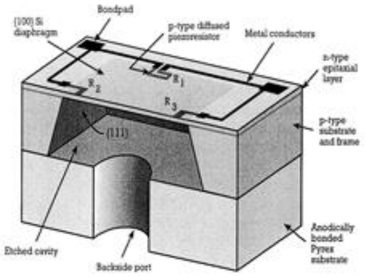

Fig.3. Fabrication of the piezoresistive pressure sensor

A cross sectional view of fabrication of a pure silicon based piezoresistive pressure sensors using a standard silicon IC process is shown in the Fig.4. The process of patterning the thin uniform layer of silicon substrate on the wafer surface. The pure silicon is hardened by baking and then selectively removed by projection of light through a reticle containing mask information. To form the diaphragm selectively removes unwanted material from the surface of the wafer using wet-etching technique. In oxidation process wet oxidation molecule convert silicon on the top the wafer to silicon dioxide. After the deposition of silicon dioxide layer piezoresistors are placed on the diaphragm by diffusing the P-type silicon to form bridge between the piezoresistors.

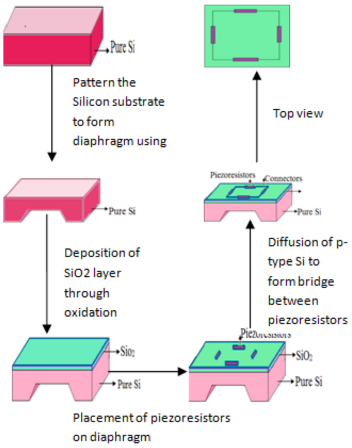

Fig.4. Cross sectional view of fabrication ofpiezoresistive pressure sensor

VIII. CONCLUSION

Research activity in the areas related to the piezoresistive pressure sensor is very broad and it has made a phenomenal growth. In this paper, an attempt has been made to provide a review on piezoresistive based pressure sensors, their various mechanisms, materials used to design the piezoresistive pressure sensor, different fabrication process; performance parameters for the piezoresistive pressure sensors are discussed. The piezoresistive pressure sensor based on Wheatstone bridge circuit is widely used by many reported works. The exceptional properties, which allow piezoresistive pressure sensors to be used in sensors, has also been reviewed. MEMS pressure sensor based on piezoresistive transduction mechanism has lot of scope due to its high sensitivity, stability and high temperature.

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