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A critical review on design of MEMS based piezoresistive pressure sensor

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ABSTRACT

One of the first MEMS devices to be commercialized is Piezoresistive pressure sensors. Piezoresistive pressure sensors are simpler to integrate with electronics, they are inherently shielded from RF noise and their response is more linear while compared to capacitive pressure sensors. Whereas, piezoresistive devices have always dominated the pressure sensor market. A silicon dioxide layer for isolation of piezoresistors from bulk is used in a Polysilicon based pressure sensors. Thereby reducing the leakage current compared to the p–n junction isolation in Si piezoresistors. This paper focuses on the review of piezoresistive pressure sensor principles, design, modeling, parameters to consider, materials that can be used in fabrication. Few models of piezoresistive pressure sensors have been simulated and the results are presented.

Keywords: MEMS, Piezoresistivity, pressure sensor, design considerations

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INTRODUCTION

Pressure sensors have become an integral part knowingly or unknowingly of various applications like automotive industry, chemical/oil and gas processing, aerospace applications, industrial measurement and control systems, etc.

The major applications of pressure sensors can be discussed as follows:

1. Pressure sensing: For metrology, aerospace, automobiles, and any other machinery that has functionality of pressure measurement as critical parameter
2. Altitude sensing: For aerospace applications such as aircraft, spacecrafts, satellites, weather balloons, and many other applications. This indicates changes in pressure relative to the altitude
3. Level sensing: Just as altitude, it can similarly be used for depth or level sensing
4. Flow sensing: to measure flow as in venture meter
5. Leak testing: To detect the pressure due to a system leak

MEMS based pressure sensors have replaced the traditional pressure sensors because of better sensor characteristics and small size[1]. There are various sensing principles which can be employed for measurement of pressure, which are two broadly categorized types:

Force collector: These are the analog types of pressure sensors which typically use a force as stimulus such a piston, diaphragm, bourdon tube or bellows to measure deflection or strain due to applied force over an area (pressure).

- Piezoresistive: It employs the phenomenon of change in resistivity of certain materials, silicon, silicon carbide, polysilicon, carbon nanotubes, silicon nano-wires, diamond, etc. Generally, this type is connected to form a Wheatstone bridge circuit to maximize the sensitivity and to reduce errors and non-linearity.
- Capacitive: It makes use of parallel plate capacitive transduction principle, where applied pressure creates change in the capacitance between two plates. By using a diaphragm and pressure cavity to create a variable capacitor and to detect strain due to applied pressure, capacitance decreasing as pressure deforms the diaphragm.
- Electromagnetic: Measures the displacement of a diaphragm by means of changes in inductance (reluctance), LVDT, Hall Effect, or by eddy current principle.
- Piezoelectric: Uses the piezoelectric effect in certain materials such as quartz to measure the strain upon the sensing mechanism due to pressure. This technology is commonly employed for the measurement of highly dynamic pressures.
- Optical: Techniques employ the use of the physical change of an optical fiber to detect strain due to applied pressure. Typically it utilizes Fiber Bragg Gratings.
- Potentiometric: It uses variable resistance, which is the motion of a wiper along a resistive mechanism and detects the strain caused by applied pressure.

Other types

These types of electronic pressure sensors use other properties (such as density) to infer pressure of a gas, or liquid.

- Resonant: This type deals with the changes in resonant frequency as the sensing mechanism to measure stress, or changes in gas density, caused by applied pressure. This technique gives better linearity and sensitivity[3].
- Thermal: The changes in thermal conductivity of a gas due to density, changes to measure pressure is used.
- Ionization: Measures the flow of charged gas particles that is ions, which varies due to density changes to measure pressure.

PIEZORESISTIVITY

The phenomenon by which the electrical resistance of a material changes in response to mechanical stress is known as piezoresistivity (Smith 1954). Piezoresistivity in semiconductors is widely used in various sensors including accelerometers, cantilever force sensors, pressure sensors, and inertial sensors (Barlian et al. 2009). In stressed silicon, due to deformation there is a change in crystal potential distribution. Band diagram and the effective mass of the holes and electron is changed in turn due to this (Cohen and Bergstresser 1966). This leads to change in the carrier mobility which leads to a change in the resistance/ resistivity.

DESIGN CONSIDERATIONS FOR PRESSURE SENSOR

In this section, we share insight of the important design principles and considerations for a silicon piezoresistive pressure sensor realization.

Piezoresistors and Diaphragm

The resistor's geometry and the fractional resistivity change are related to the fractional change of resistance. In germanium or silicon, the fractional resistance change is affected significantly by the fractional resistivity change. The relative change in resistance of conductor is given by:

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t,$$

Where πl and πt are the corresponding piezoresistive coefficients and σl and σt are the longitudinal and transverse stress respectively.

The diaphragm size and thickness, along with the size, placement and shape of piezoresistors are primary considerations in the design of a pressure sensor[4]. Thin diaphragms are more sensitive than thicker diaphragms but are difficult to fabricate. Larger resolution diaphragms results in achieving higher sensitivity but increase the feature size of the device. Increasing the size and reducing the diaphragm thickness also leads to degradation in linearity. Typically, the diaphragm in a pressure MEMS based sensor is modeled as a plate anchored at the edges[6]. A plate can be considered to be relatively thin if the thickness ratio is satisfied, which is the thickness of the diaphragm to the smaller span length is less than, ideally 1/20.

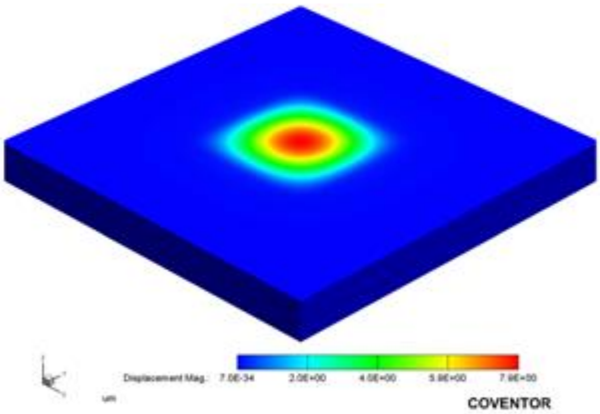

Figure 1 Diaphragm deflection

Advantages of a square diaphragm are easier to fabricate square pressure sensors at low cost using anisotropic wet etchants, better sensitivity, maximum stress is much higher, small area/space. The only disadvantage with this type is higher stress gradient and any misalignment in the placement of the resistors will affect the sensitivity drastically. Circular diaphragms show more non linearity compared to the square ones.

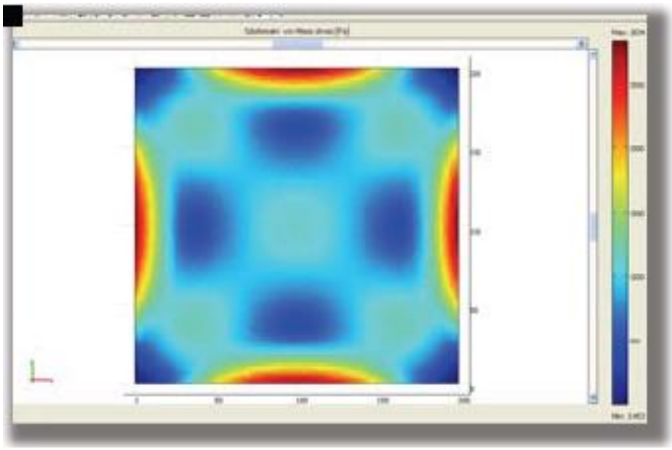

Figure 2 Square diaphragm

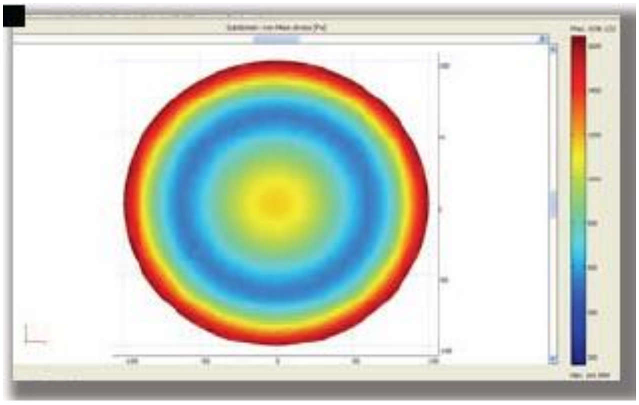

Figure 3 Circular diaphragm

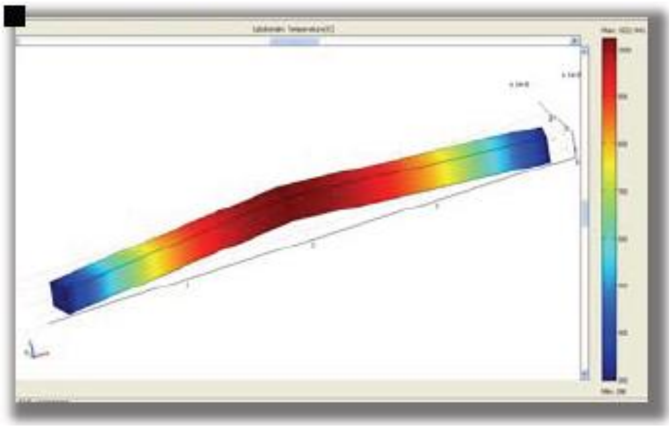

Figure 4 Beam Structure

Material selection

Several materials exhibit Piezoresistivity like silicon, polysilicon and SiC. Of all the materials, silicon is advantageous because of its small size, low weight and small power consumption. It also has wide variety of CMOS compatible process options. Silicon is widely popular with manufacturers because of the above reasons. Whereas the only disadvantage observed with them is the problem with doped piezoresistors, junction leakage at high temperatures[7]. Whereas, polysilicon piezoresistors are isolated from each other and from the bulk by oxide film, when they are connected in wheatstone bride configuration. And their disadvantages are low sensitivity, controlling and reproducibility.

Pressure range of the sensor: residual stress and fracture strength

Burst pressure of the sensor is an important aspect to be considered while designing of the sensor for a specific range of operation. Smaller diaphragms are increasingly rigid than larger diaphragm and for the same thickness of diaphragm can sustain higher pressures.

Implantation vs. diffusion

It is generally accepted that in single crystal silicon the piezoresistive coefficient is higher when P-type impurities such as boron are used for doping the resistors. Studies have proven that phosphorous diffused piezoresistors lead to higher values of sensitivity in the pressure sensors[7].

Shape and size of piezoresistors

Smaller resistors can be placed completely within high stress regions and in order to maximize sensitivity. However, while fabricating they pose the problem of precise positioning them at the right location.

Placement of piezoresistors

Smaller resistors can be placed completely within high stress regions and in order to maximize sensitivity.

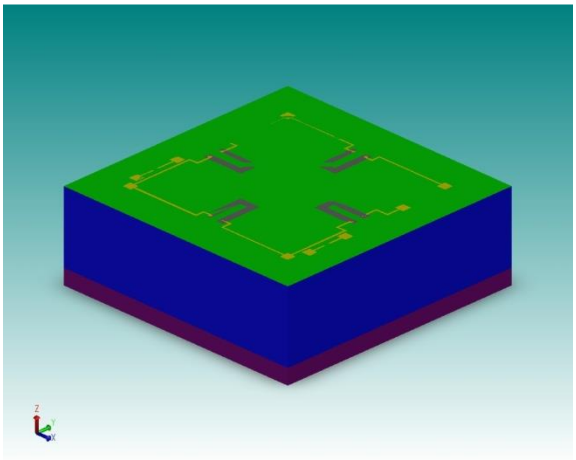

Figure 5 3D Solid view of structure

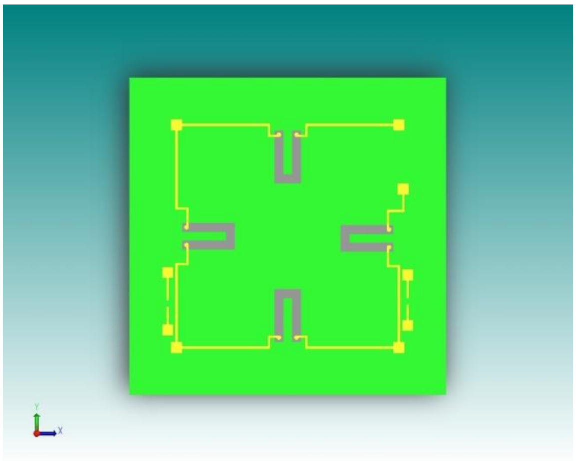

Figure 6 Top view of structure

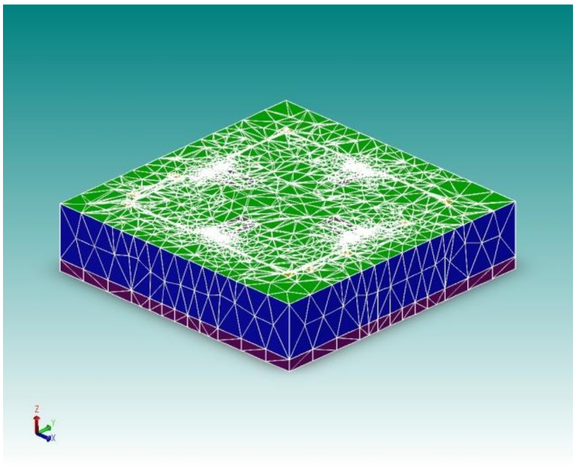

Figure 7 Mesh analysis

Taking connections from piezoresistors

To ensure a clean signal, these lines shall be aligned along the <100> orientation, where the piezoresistive effect is almost zero in case of p-type doping[12].

Figure 8 Final structure after fabrication

DISCUSSIONS AND CONCLUSIONS

This paper focuses on the review of piezoresistive pressure sensor principles, design, modeling, parameters to consider, materials that can be used in fabrication. Through this work, an overview on design methodology is discussed for silicon piezoresistive based square diaphragm pressure sensor based. The design principles and flow can be optimized based on the parameters discussed. They can be generalized for design of other pressure sensors with different fabrication techniques and/or size and shape of different elements of the sensor. The paper presented a critical survey on MEMS pressure sensor types and the design considerations.

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