Sensor Market Trends
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International Frequency Sensor Association (IFSA).
Design, Fabrication and Performance Simulation for MEMS Based Piezo-Resistive Pressure Transducers with Sensitivity and Temperature Dependency

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Abstract: The present paper describes the design, fabrication and performance of surface micromachined piezo resistive type pressure sensors. The sensors are square and circular shaped. In the first case the piezo resistive material in the form of a wire is placed on the top of a square shaped as well as circular shaped diaphragm and in the second case the wire is embedded within the two different structures.

Fabrication process follows the technique of surface micromachining. After successful completion of fabrication the structures are finally prepared for different static analysis. The I/O characteristic of the pressure sensors changes with ambient temperature. If current density of the piezo resistive material is changed there is a change in temperature which is nothing but the conversion of electrical dissipation to heat due to electrical current flowing across an interface. The deflections of the diaphragms (for square as well as circular) have also been studied for different applied pressure. From this, the operating range as well as the sensitivity of the sensors can be easily calculated. A detailed analysis of the potential with different applied pressure is presented graphically. The simulation of the proposed sensor has been carried out using Intellisuite™ software.

Keywords: MEMS Based Piezo-Resistive Pressure Transducers; Pressure sensors; Surface micromachining, MEMS
1. Introduction

Micro-electromechanical systems (MEMS) is a technology that combines computers with tiny mechanical devices such as sensors, valves, gears, mirrors, and actuators embedded in semiconductor chips. Sometimes it is said that MEMS will be “the foundational technology of the next decade”. MEMS are also called as smart matter. MEMS promises to revolutionize nearly every product category by bringing together silicon based microelectronics with micromachining technology, thus making possible the realization of complete systems on a single chip.

One of the most useful sensors for next generation electronic systems is the silicon pressure sensor, because of its wide field of application from health care to transportation. Silicon thin film piezoresistive pressure sensors appear very popular in automobile industry. High precision pressure sensors are very much required for Instrumentation systems and robotics. Experiments had been carried out on piezo-resistive pressure sensor with advent of different techniques of micro-technology. One of the popular models of micro pressure sensor is diaphragm based MEMS piezo resistive pressure sensor.

In this present paper two separate structures have been fabricated by depositing the piezoresistive wire on the top of the diaphragm and within the diaphragm i.e. in embedded form. These two fabrications are applicable for both square and circular shaped diaphragms.

2. Fabrication Process of Diaphragm Based Piezoresistive Pressure Sensor

2.1. Pressure Sensor with Resistive Wire on the Top of the Diaphragm

Single crystal silicon, so far used as the unique microelectronic material for VLSI, has been recommended as an excellent mechanical material for fabricating micro-mechanical sensors and actuators.

2.1.1. For square shaped diaphragm

Mask designing is the first stage of fabrication. A square shaped Silicon (Czochralski 100) crystal of thickness 50 micrometer has been taken as a sacrificial layer. The upper level of silicon is etched to clean. At the top of the crystal a thin layer of Silicon nitride of 0.8 µm has been deposited. After that a 0.5 µm layer of LPCVD of polysilicon has been deposited. Perfect mask designing is very much essential for lithography in the process of fabrication.

2.1.2. For circular shaped diaphragm

Here also a square shaped Silicon (Czochralski 100) crystal of thickness 50 micrometer has been taken as a sacrificial layer. A circular mask of radius 50 micrometer has been applied on the crystal. After etching a circular structure has been formed. The rest of the process is similar to that of square shaped diaphragm. The only difference lies with the mask designing. The shape of the mask is circular here. After etching polysilicon and silicon layer pressure sensor is achieved as shown in Fig. 1.
Step 1. Si crystal is etched to clean the surface.

Step 2. Si$_3$N$_4$ thin film is deposited on Si.

Step 3. Poly Silicon is deposited on Si$_3$N$_4$ layer.

After lithography and etching finally pressure sensor is achieved.

Fig. 1. Fabrication of the piezoresistive pressure sensor with resistive wire on the top of the diaphragm both for square shaped & circular shaped structure.

2.2. Pressure Sensor with Resistive Wire Embedded into the Diaphragm

The procedure of fabrication is more or less similar with the previous one. Only difference lies with the lithography. Here polysilicon is deposited after lithography. It is to be noted that for lithography of embedded structure negative photo resist has been used. The structures after fabrication are shown in Fig. 2. Now after fabricating the both square and circular shaped structure (Pressure sensor) and simulating the above, the pressure sensor is achieved as shown in Fig. 2 for square and circular shaped diaphragms respectively.
After Lithography and etching.

After deposition of polysilicon & etching silicon substrate finally pressure sensor is achieved.

**Fig 2.** Simulation of fabrication of the piezoresistive pressure sensor with resistive wire embedded into the diaphragm both for square shaped and circular shaped structure.

### 3. Electromechanical Characterization of Diaphragm Based MEMS Piezoresistive Pressure Sensors

#### 3.1. Mechanical Characterization of Silicon Nitride Diaphragm

In Figures 1 and 2 the piezoresistive polysilicon sensing element deposited on the silicon nitride diaphragms, used as a piezoresistive pressure sensors and in second case the piezoresistive polysilicon sensing element embedded into the silicon nitride diaphragm act as piezoresistive pressure sensors. The deflection change in the diaphragm causes the change in potential of the pressure sensitive polysilicon resistor. In order to characterize the piezoresistivity of polysilicon, it is very important to calculate the deflection and strain distribution in the diaphragm with respect to applied pressure.

Measurement of the deflection at the center of the diaphragms due to input pressure variation is shown in Fig. 3. Simulation results showed that the deflection increased with applied pressure as theoretically predicted.

From the figure above, it is clear that with increase in pressure, the deflection of diaphragm is much more when the piezoresistive wire is embedded into the diaphragm than when it is on the top of the diaphragm. So corresponding strain ($\varepsilon_b$) when the piezoresistive wire is embedded on the diaphragm is more than the strain ($\varepsilon_t$) when the piezoresistive wire is on the top of the diaphragm i.e. ($\varepsilon_b > \varepsilon_t$).

After simulation the deformed structures are shown in following Fig. 4.
To find the analytical solution, deflection \( w \) of a clamped circular plate under a uniform applied pressure \( P \) is given by [6]:

\[
W = \frac{Pa^4}{64D} \left[1-(\frac{r}{a})^2\right]^2, \tag{1}
\]

where \( r, a \) are the radial coordinate and diaphragm radius, respectively. \( D \) is the flexural rigidity and is given by [6]:

\[
D = \frac{Eh^3}{12(1-\nu^2)}, \tag{2}
\]

where \( E, h, \nu \) are Young’s modulus, plate thickness, and Poisson’s ratio, respectively. Eq. (1) and (2) shows that the diaphragm will exhibit a maximum strain at the center as shown in Fig.4.

### 3.2. Potential-Pressure Dependency

The variation of potential with applied pressure is observed with two different thermal conditions.
3.2.1. Without temperature compensation

Figs. 5 and 6 show potential pressure dependency of the square and circular shaped pressure sensors with two different positions of piezoresistive material on the diaphragms under different pressure.

**Fig. 5.** Potential pressure dependency of the square shaped pressure sensors with heat sink.

**Fig. 6.** Potential pressure dependency of the circular shaped pressure sensors with heat sink.

These plotting show that as pressure increases potential of the deposited polysilicon wire increases for both the structures whereas potential of the embedded polysilicon wire decreases or remain same as pressure increases. But the rate of decreasing in potential is very much less as compared to the increasing one.

3.2.2. With temperature compensation

Here a heat sink has been added to keep the diaphragm at a constant temperature 20°C. The figures below (Figs. 7 and 8) show the potential pressure dependency where the effect of variation of temperature on the potential is eliminated.
Fig. 7. Potential pressure dependency for square shaped diaphragm without heat sink.

Fig. 8. Potential pressure dependency for circular shaped diaphragm without heat sink.

From the above figures it is clear that the behavior of the curves with and without heat sink is more or less similar for square and circular shaped pressure sensors. It is proved that with increase in pressure output voltage (potential) is more for the piezoresistive wire, which is on the top of the diaphragm than that for piezoresistive wire, which is embedded into the diaphragm for both the structures. Here for a known current the ratio of change in resistance with initial resistance (i.e. $dR/R$) of the piezoresistive wire is calculated from the change in potential. In this case with increase in pressure $dR/R$ is more for the piezo-resistive wire, which is on the top of the diaphragm than that for piezo-resistive wire, which is embedded into the diaphragm i.e.

$$(dR/R)_t > (dR/R)_b.$$ 

So finally it can be written that,

$$(dR/R)_t (1/\varepsilon_t) > (dR/R)_b (1/\varepsilon_b)$$

i.e.

$$(G.F)_t > (G.F)_b.$$ 

This means the sensor will be more sensitive with pressure variation when the piezo-resistive wire is on the top of the diaphragm rather than when the piezo-resistive wire embedded into the diaphragm.

3.2.3. Temperature - current dependency

If we change the current density of the piezo resistive material, the mobility of ions increases which generates heat. Temperature increases due to this heating.
The characteristic (Fig. 9) shows how maximum temperature changes with the change in current density. The peak temperature changes maximum when the piezoresistive wire is embedded into the diaphragm rather than when it is placed on the top of the diaphragm.

Here we consider that heat is flowing through the process of conduction only again we know,

\[
\left( \frac{\partial H}{\partial t} \right) = -k \int \Delta T \, ds,
\]

where \( H \) is the amount of heat transferred; \( t \) is the time, \( k \) is the conductivity, \( T \) is the temperature, \( S \) is the area through which the heat is flowing.

![Figure 9. Temperature current relationship in piezoresistive transducer.](image)

When the resistive wire is in deposited form, heat can be conducted from the lower surface of the transducer only, whereas in embedded form of resistor the conduction of the heat can be generated by the three sides. So the temperature hikes in deposited structures are less than that of embedded structures as the amount of heat transferred directly depends upon the surface area.

It has been reported that I-V curve of a polysilicon follows the following relationship

\[
V_s = 2 \sqrt{\frac{K_e \rho_s \tan \left( \sqrt{\frac{J \rho_s \xi}{K_e}} \frac{l}{2} \right)}},
\]

where \( V \) is the applied voltage, \( J \) the current density, \( \rho_s \) is the ploy-resistivity \( K_e \) is the thermal conductivity, \( l \) is the length and \( \xi \) is the temperature coefficient of the poly resistor. By solving Eq (3) the current \((I_1=J \times \text{Area})\) is calculated. However Eq. (3) does not account for the change in polyresistance, which is due to self heating. It has been reported [9] that with the increase of current, power dissipation through the polysilicon film increases. This results in a decrease of grain boundary barrier. The temperature of the polysilicon film also increases with an additional current flow due to lowering of the grain boundary. The temperature of th film is calculated from

\[
T=T_A+VI_1/IK_e,
\]
where $I_1$ is the current calculated from Eq. (3) and $T_A$ is the ambient temperature of the polysilicon film. First the temperature of the film is calculated from Eq. (4) and then the increase of current ($I_2$) due to the increase of temperature is calculated by

$$I_2 = \frac{1}{V} K_e (T - T_A) \quad (5)$$

4. Conclusion

The present work has focused on the fabrication and comparative analysis of the two different shaped pressure sensors. In fabrication two alternative approaches has been presented over here for these structures. With increase in pressure, the diaphragm is deformed with corresponding change in the resistance of the wire. Results from the simulations and experiments clearly demonstrate a comprehensive system optimization. Electromechanical analysis of the two pressure sensors has done. In the analysis it has been found that, strain is more in the case when the resistive wire is embedded into the diaphragm than the strain when the resistive wire rest on the diaphragm. Again with increase in the pressure output potential as well as the ratio of change in resistance to the initial resistance is more for the piezoresistive wire deposited on the diaphragm than that for the piezoresistive wire embedded on the diaphragm. So, gauge factor is more for the pressure sensor where the resistive wire rest on the top of the diaphragm.

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References

Aims and Scope

*Sensors & Transducers Journal (ISSN 1726-5479)* provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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‘This book provides a good basis for anyone entering or studying the field of smart sensors not only for the inexperienced but also very useful to those with some experience’

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