Fabrication and Characterization of Pressure Sensor, and Enhancement of Output Characteristics by Modification of Operating Pressure Range

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***Abstract*— Pressure microsensors are very frequently used for applications encompassing a wide range of operating pressure ranges. However, it is possible to use the same pressure sensor for different operating ranges (in a limited range) with satisfactory performance. In this work, we report the possibility of using a single sensor for different pressure ranges. Operating the sensor at a lower pressure range not only offers flexibility of usage but also enhances output performance in terms of sensitivity and linearity. The concept is demonstrated using a pressure sensor with implanted polysilicon piezoresistors and bulk micromachined diaphragm fabricated using a standard process. The characterization data of the sensor is analyzed for three pressure ranges (10 Bar, 20 Bar and 30 Bar). The results show that modifying the full scale pressure of operation from 30 to 10 Bar increases the sensitivity from 6.03 mV/Bar to 6.58 mV/Bar. The non-linearity is also reduced by an order of magnitude from 3.89 % to 0.33 %.**

Keywords*— Piezoresistive pressure sensors; polysilicon piezoresistors; sensitivity and linearity enhancement

I. INTRODUCTION

Pressure sensors employing the piezoresistive transduction mechanism are popular due to several advantages like small size, high sensitivity and simple DC output [1]. The applications of pressure sensors can encompass a broad range of pressure ranges. Applications such as oil well pressure measurement [2], explosion pressure measurement [3] etc. have high pressure ranges whereas barometric pressure sensors [4] and those used for biomedical applications [5] operate at low pressures. Piezoresistive pressure sensors have smaller size and are less bulky compared to their traditional counterparts. The market demand for these sensors is continually on the rise due to the above mentioned advantages. There are specific requirement for each sensor application and thus the sensor design for a particular pressure sensor is usually unique [6]. The sensor design optimization involves optimizing the diaphragm size, shape, thickness and the piezoresistor position. Using a sensor designed for lower range for high pressure operation may lead to good sensitivity but a degraded linearity. Also, the sensor diaphragm may get ruptured as the thickness used may not be sufficient to sustain such higher pressure. Similarly, using a high pressure sensor for low pressure ranges may greatly enhance the linearity but the sensitivity requirement may not be fulfilled. However, it is possible to use a single pressure sensor for different pressure ranges in a limited pressure span if the sensitivity and non-linearity is acceptable for the pressure ranges. In this work, the fabrication and characterization of a polysilicon piezoresistive pressure sensor is described. Using the characterization results of the fabricated sensor, enhancement in sensitivity and linearity of the sensor at lower pressure ranges compared to the values at high pressure range are reported.

II. PRESSURE SENSOR OPERATION AND STRUCTURE

The operation of a piezoresistive pressure sensor is based on change in resistance of four piezoresistors arranged on a diaphragm in Wheatstone bridge configuration. When the diaphragm is under stress, being subjected to pressure, two piezoresistors experience a relative increase in the resistance (α_1) and the other two piezoresistors experience a relative decrease in resistance ($-\alpha_2$) from their values in unstressed state. The change in resistance is caused by a change in the resistivity of the semiconductor due to stress. The output voltage of the pressure sensor can be given by [7]:

$$V_{out} = \frac{\alpha_1 + \alpha_2}{2} V_{in} \tag{1}$$

where V_{out} is the output voltage, V_{in} is the input bias to the Wheatstone bridge circuit and α_1, $\alpha_2 > 0$. In the present work, the sensor structure consists of a diaphragm fabricated using bulk micromachining with wet anisotropic etchant tetramethylammonium hydroxide (TMAH) leading to slanted side walls in diaphragm cavity. The sensitivity of the pressure sensor is proportional to the differential stress on the piezoresistors [8]:

$$V_{out} = \frac{V_{in}}{2} \pi_{44} (\sigma_x - \sigma_y) \tag{2}$$

where π_{44} is the shear piezoresistive coefficient and $\sigma_x - \sigma_y$ is the differential stress on the piezoresistor. Novel meander shaped polysilicon piezoresistors with oxide isolation are placed at high stress regions in diaphragm. The high stress regions are determined by finite element method based simulation using CAD tool Coventorware®. Thermal oxide provides isolation between the polysilicon piezoresistors and the bulk substrate. This enables the sensor to operate at higher temperatures compared to silicon based piezoresistors which are isolated by a p-n junction [9,10]. The piezoresistor shapes are designed to have metal lines outside the diaphragm edges for better reliability. All the piezoresistors are aligned length wise along <110> direction and are doped using ion-implantation. A square shaped diaphragm is chosen for maximum sensitivity. The edge length of the diaphragm is 1480 µm and the diaphragm thickness is chosen as 50 µm. For rupture free operation of the sensor diaphragm, the diaphragm dimensions are chosen such that the von-Mises stress on the diaphragm structure at the maximum pressure of operation (30 Bar) is less than 1/5th of the fracture stress for silicon (7 GPa). The piezoresistor shapes and sensor structure are depicted in Fig. 1.

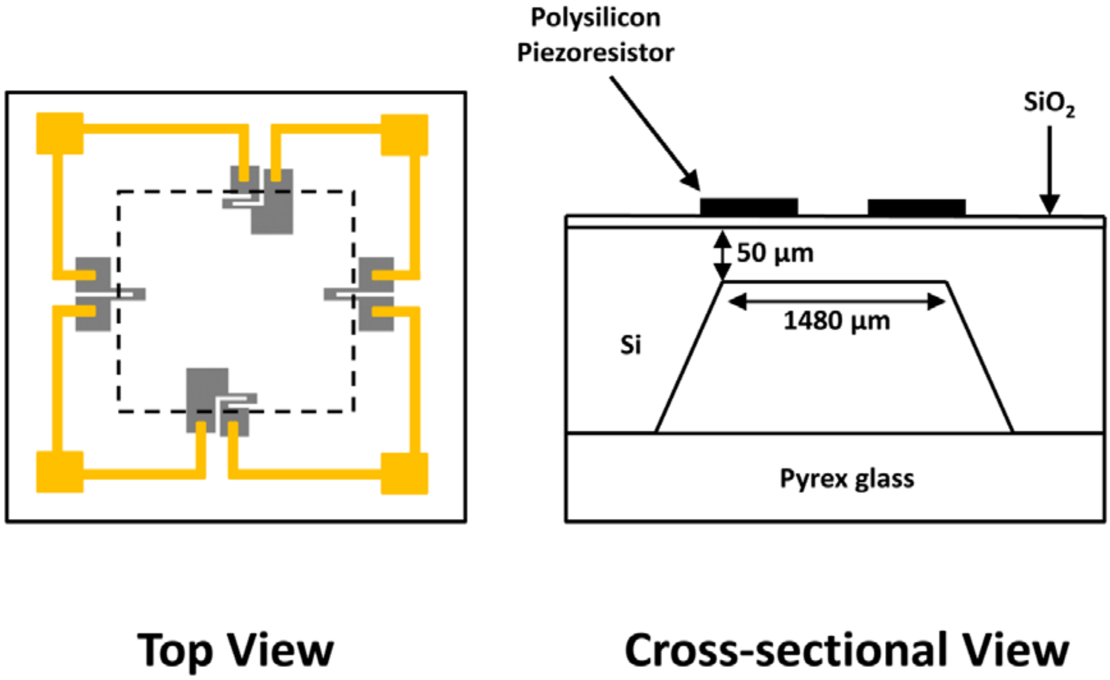

Fig. 1. Pressure sensor structure showing polysilicon piezoresistors connected in Wheatstone bridge configuration.

III. FABRICATION

A standard process is used for fabrication of the sensor. The fabrication process starts with the bulk micromachining of silicon with thermal oxide and nitride masking to form a diaphragm with a thickness of 50 µm. The etching is carried out using 25% wt. TMAH at a temperature of 85 °C. The masking oxide and nitride are subsequently etched. Thereafter 0.5 µm thick polysilicon is deposited using low pressure chemical vapor deposition (LPCVD) technique at 620 °C and patterned using reactive ion etching (RIE) to form the four polysilicon piezoresistors. The piezoresistors are isolated from each other and from the bulk by a thermal oxide layer with a thickness of 0.1 µm. Prior to patterning the piezoresistors, the polysilicon is doped with boron using ion implantation with a dose of 1.5×10^{15} atoms/cm^2 and energy of 80 keV and is annealed for 30 min. at 1000 °C in nitrogen ambient. PECVD oxide with a thickness of 0.5 µm is deposited and via holes is opened for taking out contact with the piezoresistors. During the dry etching of polysilicon, the oxide layer underneath is also etched at certain places and therefore it is necessary to deposit a PECVD layer for isolating the metal lines from the bulk. Cr/Au metallization with a thickness of 200Å/2000Å is sputtered on the wafer and it is patterned to connect the piezoresistors in an open bridge configuration. The diaphragm cavity at the back side is sealed using anodic bonding with Pyrex glass in vacuum (10^{-6} Bar) in order to obtain an absolute pressure sensor. Care needs to be taken to properly clean the silicon and glass wafer prior to anodic bonding as contamination and resist traces can lead to void formation at the bonding interface. The bonding is carried out at 325 °C with an electric field of 400 V (5 min) and 600 V (10 min). The chips on the wafer are separated by using a Disco dicing saw. The entire fabrication process is carried out using four lithographic steps. The microphotograph of the fabricated pressure sensor is shown in Fig. 2. The magnified view of the two different kind of piezoresistor shapes are also shown in the figure.

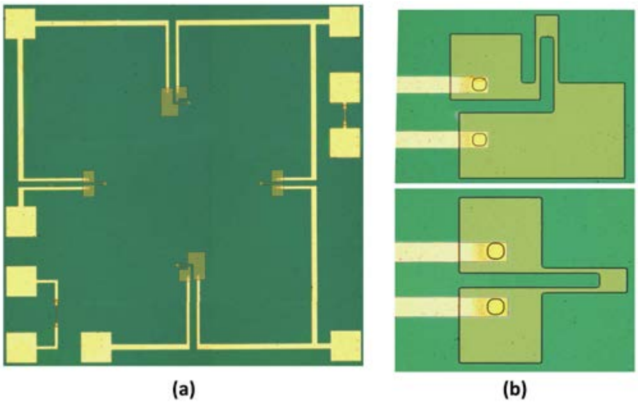

Fig. 2. (a) Microphotograph of the fabricated pressure sensor. (b) Magnified view of different piezoresistor shapes.

IV. Characterization Results and Discussion

After fabrication, the sensor is characterized at a constant temperature of 25°C inside a thermal chamber using a pressure controller. Pressure loads of 1 Bar to 30 Bar (in step of 1 Bar) are applied on the sensor which is housed inside a custom made jig with a pressure port. A voltage bias of 3.3 V is provided to the sensor and the output of the sensor is measured using a multimeter. The output characteristic of the sensor is plotted in Fig. 3.

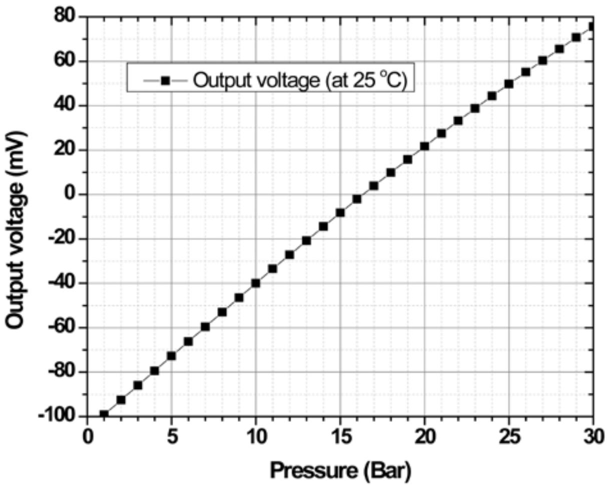

Fig. 3 Output characteristics of the pressure sensor at 25°C.

It is evident from Fig. 1 that there are two different types of piezoresistors, which are unsymmetrical in shape. This causes a mismatch of a few hundred ohms in resistance value of the two piezoresistors. Thus, it is expected that the sensor would have a high offset voltage. The offset voltage is found to be about -99.2 mV (at 1 Bar pressure). The pressure vs. output voltage curve of a pressure sensor is never a straight line and always has a non-linearity component. An exaggerated depiction of a typical performance curve of a typical sensor is shown in Fig. 4. The end point straight line method is used calculate the sensitivity of the sensor. The sensitivity of the sensor is the slope of this line connecting the voltage output at the minimum and maximum value of the pressure range [11]. The non-linearity of the sensor is the deviation of the performance curve (experimentally determined values) from the end point straight line. As can be seen from Fig. 4 as the pressure range is reduced, the sensitivity (slope of the curve) increases and the non-linearity (deviation of the performance curve) is reduced, leading to an improved performance.

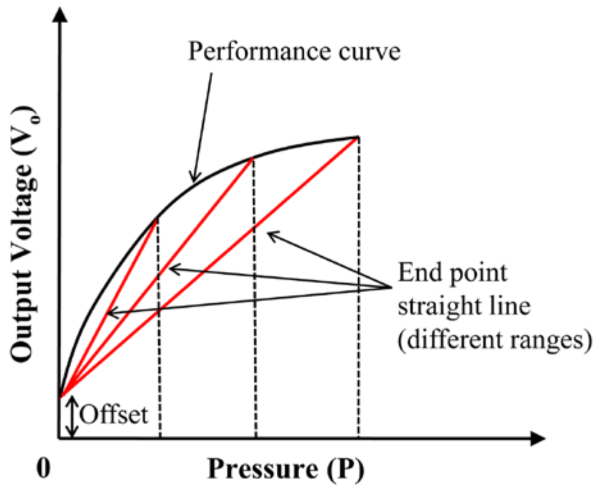

Fig. 4. Typical sensor characteristics showing the reduction in non-linearity and increase in sensitivity at lower pressure ranges.

Due to the unavailability of vacuum pump in the pressure controller it was not possible to find out the output of the sensor at vacuum. Therefore, the sensor output was extrapolated for the 0 Bar pressure for calculation of the non-linearity of the sensor using the end point straight line. The sensor non-linearity for the three pressure ranges are depicted in Fig. 5.

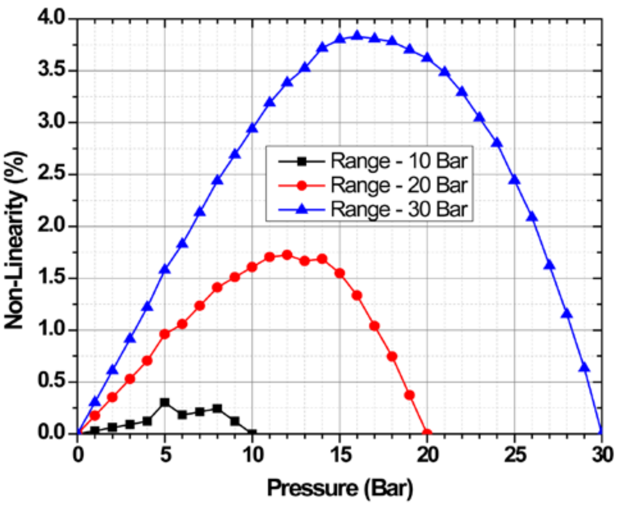

Fig. 5 Non-linearity of the pressure sensor for different pressure ranges (0-10 Bar, 0-20 Bar and 0-30 Bar).

The sensitivity and non-linearity of the sensor for the three pressure ranges, namely, 0-10 Bar, 0-20 Bar and 0-30 Bar are enlisted in Table 1. It can be clearly seen that the best sensitivity is obtained for the lower pressure range of 0-10 Bar and the non-linearity value is enhanced by an order of magnitude compared to the value for 0-30 Bar range. Thus, although the sensor non-linearity of < 3.89 % (in the pressure range of 0-30 Bar) may not be sufficient for some applications, a non-linearity of < 0.33 % (in the pressure range of 0-10 Bar) is acceptable for most of the applications in that range. Although a sensitivity enhancement is also obtained in this case, it is possible the sensitivity of the sensor may not increase significantly or even reduce in some other cases. However, the sensitivity change may not be very significant in most of the cases. Also, the non-linearity shows a marked improvement and therefore the sensor can be used for a lower range with a much linear performance.

TABLE I. SENSITIVITY AND NON-LINEARITY OF THE SENSOR FOR DIFFERENT PRESSURE RANGES AND DIFFERENT TEMPERATURES

Pressure Range (Bar)	***Sensitivity (mV/Bar)***	***Non-linearity (%/full scale)***
0-30	6.03	< 3.89
0-20	6.36	< 1.79
0-10	6.58	< 0.33

V. CONCLUSIONS

This paper discusses the enhancement in sensitivity and linearity of a polysilicon piezoresistive pressure sensor. The fabrication and characterization of the sensor are also discussed. The results open up the possibility of using the same sensor for different pressure ranges within a limited pressure span based on the requirement and specifications.

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