2. Piezoresistive Pressure Sensor

2.1 Piezoresistive Pressure Sensor Design

Piezoresistive pressure sensor was one of the first devices using a silicon piezoresistive gauge. The general diagram of this kind of a sensor, shown in Figure 2.1, provides differential pressure measurement and optionally gauge pressure measurement if the input 2 is closed under the atmospheric pressure conditions, and absolute pressure measurement in the case when the input 2 is vacuum sealed.

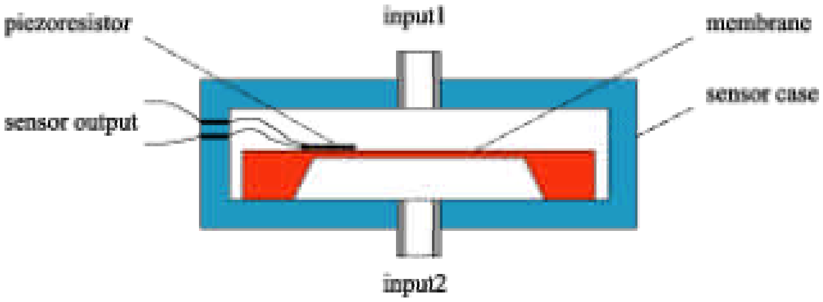

Figure 2.1. Differential piezoresistive pressure sensor.

The sensor fundamental part is a plate of silicon or polysilicon equipped with one or several piezoresistives gauges. This plate, often called membrane, shows a deformation that is a function of a pressure difference between its two sides. The pressure difference induces a stress variation in the plate. The resulting stress is then measured by piezoresistive gauges that are placed in specific places of a plate. Piezoresistors can be diffused in silicon plates with different crystal orientations, along many crystal directions. In order to make an optimal choice of a piezoresistive sensor location, the stress pattern on the surface of the plate deformed by the pressure difference should be known.

The stress pattern depends basically on the geometrical form of the plate. A **circular form** is the simplest one in terms of stress estimation. When a pressure difference on both sides of a circular plate is small, a linear approximation can be made, which means that only bending but no stretching of the plate is assumed. There are tensile stresses at the edges, whereas compressive stresses are in the centre. The stresses are assumed either in the radial or in the tangential direction. In the centre, radial and tangential stresses have the same magnitude. For both stresses, a certain radius can be found for which the stresses are zero and a corresponding value of the stress on the edges can also be determined.

A circular plate that is symmetrical and easy to analyse is difficult to obtain in (100) planes by micromachining. From a fabrication point of view, a **square form** of plates has some advantages. The calculation of stress and deflection in a square plate requires numerical analysis and simple analytic functions cannot be obtained. The square plate behaves similarly to a circular plate in the centre, but at the edges, the stress is more concentrated towards their centres. This fact may have as a consequence ruptures of square plates in lower pressure differences.

A **ring form,** obtained if the centre part of a plate is not etched, can be considered for certain applications where only small pressure differences have to be measured. In such a ring structure, stresses are due more to bending than to stretching thus limiting a nonlinear behaviour.

Once the form of the membrane is decided, we can consider placing the piezoresistive gauges. The geometrical design is important for the optimal sensor performance. In general, four piezoresistors are used, as shown in Figure 2.2, where three different configurations are depicted.

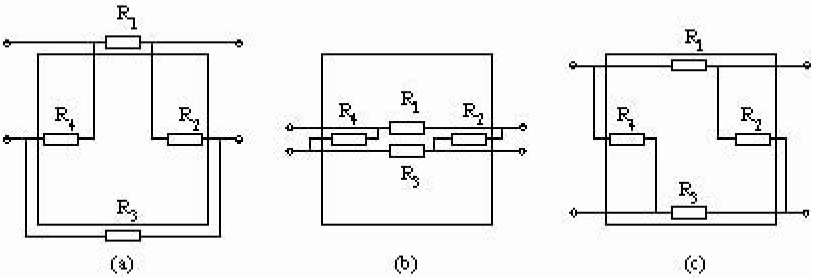

Figure 2.2. Piezoresistive gauges configurations.

The gauges R2 and R4 in the Figure 2.2a are placed close to the centre of the membrane edges where the maximal stress in the direction perpendicular to the membrane edge is expected. These resistors are oriented so that they sense the stress in the direction parallel to the current traversing them. The resistors R1 and R3 are outside the membrane and thus they are not exposed to the stress related to the membrane deformation. In this solution, the presence of the reference resistances R1 and R3 on a same chip as R2 and R4 can be used for temperature compensation.

The configuration shown in Figure 2.2b has the same advantage in terms of the temperature compensation as the previous one. Moreover, it shows up higher sensitivity because of two resistances placed in the centre of the membrane where the stress is of the opposite sign comparing to the edges. This fact will bring higher resistance variation in Wheatstone bridge arrangement.

When piezoresistors are made of silicon, the set-up shown in Figure 2.2c can be used. Similarly to the arrangement of Figure 2.2a, two gauges R2 and R4 are sensitive to the stress in the direction perpendicular to the membrane edge and parallel to their current. Two other gauges are placed to sense the stress perpendicular to their current flow. An important feature of this configuration is that the resistance change of the first two piezoresistors will always be opposite to that of the other two, which increases of the sensor sensitivity.

The most of commercially available micromachined pressure sensors are **bulk micromachined piezoresistive devices**. These devices are etched from single-crystal silicon wafers, which have relatively well-controlled mechanical properties. The piezoresistors are fashioned by selectively doping portions of the diaphragm to form junction-isolated resistors. Although this form of isolation can permit significant leakage current at elevated temperatures and the resistors present sheet resistance per unit length that depends on the local bias across the isolation diode, it permits the designer to exploit the substantial piezoresistive coefficient of silicon and locate the resistors at the points of maximum stress on the diaphragm.

Surface micromachined piezoresistive pressure sensors have also been reported. The structural material for the diaphragm may be either silicon nitride or polysilicon. This fabrication approach permits small devices with high packing density to be fabricated. However, the maximum deflection of the diaphragm is limited to the thickness of the sacrificial layer and can constrain the dynamic range much like the capacitive device.

Most of piezoresistive pressure sensors consist of a Wheatstone bridge with four piezoresistive elements on a thin silicon membrane. In the following configuration, developed by Motorola, the Wheatstone bridge is replaced by a cross-shaped piezoresistive element with four connections, as shown in Figure 2.3.

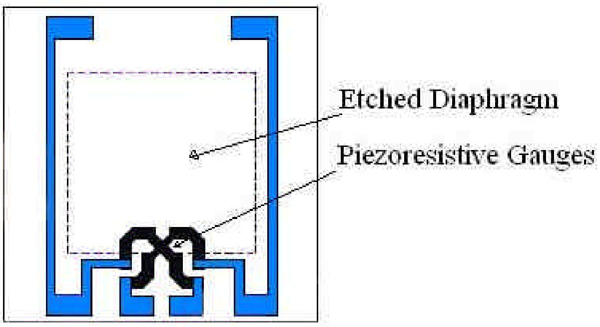

Figure 2.3. Plan view of Motorola "X-ducer" silicon pressure transducer.

2.2 Temperature Sensitivity of Piezoresistive Pressure Sensors

Temperature sensitivity is a major concern for piezoresistive sensors, since the piezoresistance effect is inherently temperature dependent. Therefore these types of sensors often require temperature-compensation circuitry, especially if used over an extensive temperature range. There are different ways that can be employed for the temperature compensation.

To reduce the temperature coefficient of offset (TCO), the Wheatstone bridge configuration was shown to be effective, since temperature changes result only in common-mode effects, which mean that all resistors in the bridge change equally and the output of the bridge does not change.

The most significant temperature error is the temperature coefficient of sensitivity (TCS). Therefore, in the main field of applications it is sufficient only to compensate TCS. The easiest solution is using a constant current source supply for the bridge. With increasing temperature the bridge resistance is increasing too. The rise of the supply voltage increases the output voltage which is ratiometric to the supply voltage. Since the values of TCS and temperature coefficient of resistance (TCR) are similar but of opposite signs, the change of sensitivity due to temperature is almost compensated. Another solution is the passive temperature compensation using simple resistor networks. The passive compensation can be used for the temperature ranges from 0°C to 85°C. A disadvantage of this method is a reduced output signal caused by voltage dividers. For temperature ranges from - 40°C to 125°C, more extensive compensation networks are necessary. The solution may be active temperature compensation that works with active devices which supply a temperature dependent voltage supply of the bridge or temperature dependent signal amplification.

2.3 Related Reading

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