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Research Article

Modelling of Different MEMS Pressure Sensors using COMSOL Multiphysics

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Abstract

This paper presents the basic introduction of MEMS pressure sensors. The different types of pressure and its operating principles also included. MEMS pressure sensors have widely used in automotive, biomedical and industrial applications. The design and simulation of different pressure sensors such as capacitive, piezoelectric and piezoresistive MEMS pressure sensors are also proposed in this paper. The COMSOL Multiphysics software is used for the designing and simulation of different MEMS Pressure sensors.

Keywords: *Pressure sensors, capacitive pressure sensors, piezoresistive pressure sensors, piezoelectric pressure sensors, MEMS*

1. Introduction

Pressure is an important parameter in our real life applications. Pressure is represented as force per unit area; the mathematical expression of pressure, P is given by:

$$P = \frac{F}{A}$$

Where F is applied force and A is area where the force is applied.

Pressure sensors generally use a pressure sensitive element (such a diaphragm, piston, bourdon tube, or bellows). So when a pressure is applied to the sensor, pressure sensitive element is deformed, that produces electrical signal at output; this is a basic principle of any pressure sensor.

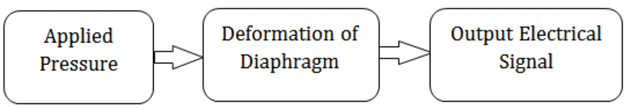

Figure.1 Basic Principle of pressure sensor

MEMS or Micro-Electro-Mechanical system is a fabrication technology used to create a micro scale integrated device or system that combine electrical and mechanical components. The size of MEMS fabricated devices are from few micrometers to millimeters. These devices are able to sense, control and actuate on the micro scale and generate effects on macro scale (A Ghosh *et al*, 2013). MEMS device consist of microstructures, microsensors, microactuators and microelectronics, all integrated onto the one single silicon chip. A microsensor detects any changes in physical quantity such as temperature, pressure and provides electrical signal at output. Microactuators to react and create some form of changes to the environment, and Microelectronics is used for signal conditioning in MEMS (P.K.Rathore *et al*, 2013). In MEMS pressure sensor materials used for fabrication are in micro sized. These MEMS pressure sensors used in various field such as biomedical application, automotive industry, and control industry.

2. Classification of Pressure Sensors

The pressure sensors are classified according to its sensing element used. This includes piezoresistive pressure, piezoelectric pressure sensor and capacitive pressure sensor.

(*i*) *The piezoresistive pressure sensors* are those which detect the change of external pressure by changing its resistance (P.K.Rathore *et al*, 2013). The piezoresistive pressure sensor consists of a semiconductor material (silicon) mounted on the elastic diaphragm as shown in Fig. 2. This semiconductor material acts as piezoresistive sensing element in the pressure sensor. When pressure is applied then the diaphragm is stretched and deformed, the piezoresistive element will change its resistance. When a pressure is applied, the diaphragm is flexed as well as the piezoresistive material. Therefore, the piezoresistive material

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becomes slightly longer and thinner due to applied pressure as shown in Fig. 3. This deformation results in the change in resistance of the piezoresistive material.

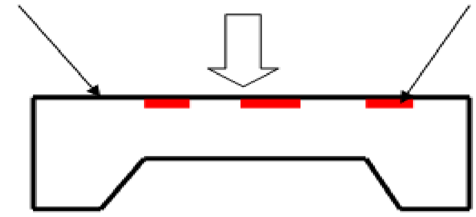

Figure 2 Piezoresistive pressure sensor

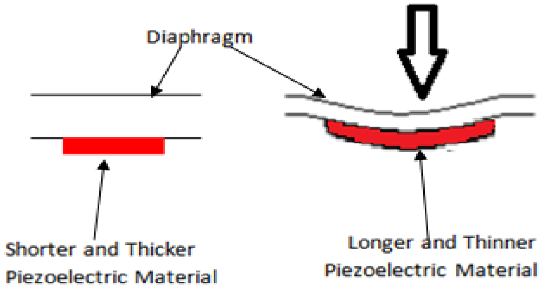

Figure 3 Deformation of piezoresistive material

The mathematical expression of the resistance, R is given by

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

Where, ρ is the resistivity of the material, L is the length of the piezoresistive material and A denotes the cross-sectional area of the piezoresistive material. Since cross-sectional area is equal to the width multiply with thickness; therefore,

$$R = \frac{\rho L}{Wt} \quad (2)$$

Where, w represents the width of the piezoresistive material and t represents the thickness of the piezoresistive material. Since the piezoresistive material becomes longer and thinner when it is subjected to a pressure, from equation-2, it can be said that the resistance of the piezoresistive material is increased. The piezoresistive pressure sensor is normally implemented together with Wheatstone bridge circuit is used to convert the resistance changes into the change in electrical potential. The Wheatstone bridge also provides some advantages to the pressure sensor for example provides more linear output, maximizes the sensitivity of the sensor and minimizes the error of the sensor.

From Fig. 4, the ΔR is the resistance change of the piezoresistive pressure sensor and the R is a re fixed resistance. Hence, the expression of output voltage in Fig. 4 is given by:

$$Vout = \frac{-(0.5\,\Delta R)V_{in}}{(2R+\Delta R)} \quad (3)$$

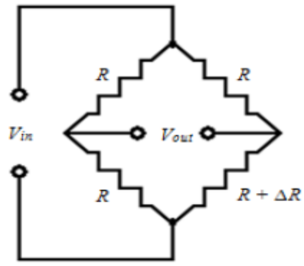

Figure 4 Piezoresistive pressure sensor in Wheatstone bridge

Where, Vout is the output voltage of Wheatstone bridge and Vin the input voltage of Wheatstone bridge. Thus, by measuring the output voltage of Wheatstone bridge, the change in pressure can be determined.

(ii) A piezoelectric pressure sensors are detecting the applied external pressure by changing its electrical potential as the output of sensor (V.Mohammadi *et al*, 2009). By comparing with piezoresistive pressure sensor, this pressure sensor provides only a change in electrical potential, not the change in electrical resistance. When a pressure is applied, the diaphragm of piezoelectric pressure sensor is deformed, and then electrical voltage is generated. The piezoelectric pressure sensor consists of metalized quartz or ceramic material as sensing element.

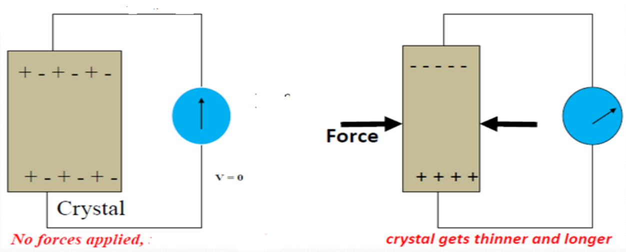

Figure 5 Piezoelectric pressure sensor

The generation of positive charges a from the crystal results in a flow of electrical charge. This means that an electrical potential is produced between the crystal and the base in the pressure sensor. The relationship between generated potential, V and the charge, Q is given by:

$$V = \frac{Q}{C} \quad (4)$$

Where C is the capacitance between the crystal and the base of piezoelectric pressure sensor.

From equation-4, it can be said that the generated voltage is directly proportional to the generated charge from the crystal. When the applied pressure in increased, more charges is generated, therefore the generated voltage is also increased. By measuring the potential difference between the crystal and the base, the value indicates the pressure that is applied to the pressure sensor. The relationship between applied pressures. The generated potential by piezoelectric pressure sensor is shown in Fig. 6.

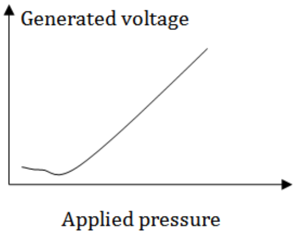

Figure 6 The relationship of applied pressure and generated potential

Normally, this type of pressure sensor is designed together with an amplifier to enhance the electrical interface. However, the piezoelectric pressure sensor is very susceptible to shock and vibration.

(iii) Capacitive pressure sensor will change in its capacitance proportionally with applied external pressure. A capacitive pressure sensor has two conductive plates, first known as measuring plate and second is reference plate. The measuring plate will be flexed when pressure is applied, whereas the reference plate is fixed at appropriate position so it acts as reference to the measuring plate. Once the measuring plate is flexed, the distance between these two conductive plates of capacitance is changed. By measuring the distance between these two plates, the value of capacitance will be known as the distance between two plates representing the value of capacitance By applying the equation of capacitance, C :

$$C = \frac{\epsilon_r \epsilon A}{d} \quad (5)$$

where , ϵ_r is relative permittivity, ϵ is dielectric constant, A is the area of the conductive plates and d is the distance between two plates (G. Meng *et al*, 1999; F. He *et al*, 2007).

Thus, from equation-5, it can be said that the capacitance is inversely proportional to the distance between two conductive plates. In other words, the higher the applied pressure, the shorter the distance between two conductive plates, the higher the capacitance is generated. The relationship between applied pressure and the generated capacitance by capacitive pressure sensor is shown in Fig. 7.

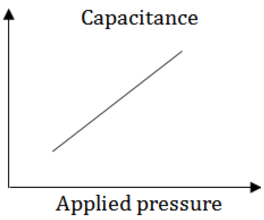

Figure 7 The relationship of applied pressure and generated capacitance

The capacitive pressure sensor has some advantages over the piezoresistive and piezoelectric pressure senor. Operation of capacitive sensor is quite stable and the output of measurement is highly linear. However, capacitive pressure sensor is very sensitive to high temperature.

3. Design of MEMS Pressure Sensors using COMSOL Multiphysics

COMSOL Multiphysics is a powerful tool for modeling and solving all kinds of scientific and engineering problems, so it is used for modeling and simulation of capacitive, piezoelectric and piezoresistive pressure sensors. MEMS Capacitive pressure sensor designed with circular radius of 180μm and composed of SiC (6H). Piezoelectric pressure sensor is also designed with circular radius of 180μm and composed of Lead Zirconate Titanate (PZT-5A). The Piezoresistive pressure sensor is designed with side length of 11μm piezoresistive pressure sensor is composed of n-Silicon (single-crystal, lightly doped) and p-silicon (single-crystal, lightly doped).

Piezoresistive pressure sensor

Piezoresistivity is the change of resistance of a material when it is submitted to stress. A piezoresistor pressure sensor measures the applied pressure on one side of the diaphragm. The stress change in the diaphragm causes the resistance to change. Fig.8 shows Piezoresistive pressure sensors

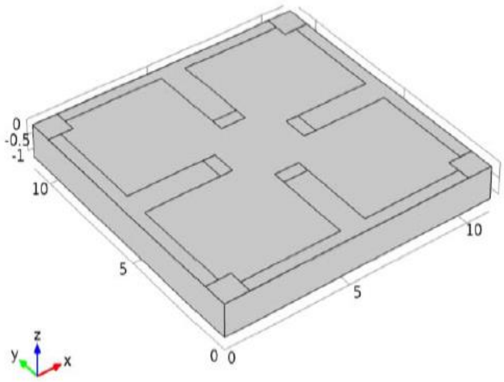

Figure 8 Piezoresistive pressure sensor

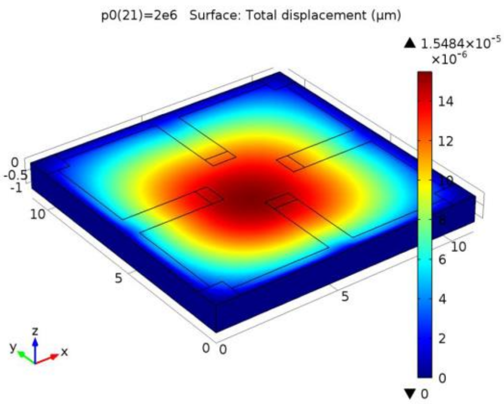

Figure 9 The model of piezoresistive pressure sensor

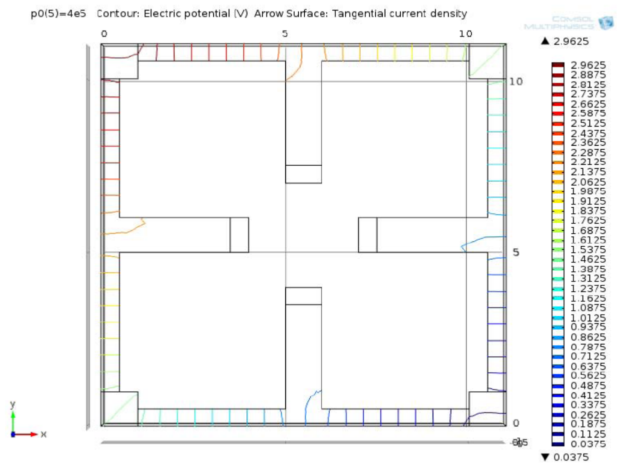

Figure 10 The distribution of voltage for applied pressure

Piezoelectric Pressure Sensor

When pressure (stress) is applied to piezoelectric crystal materials such as Barium Titanate, single-crystal quartz, and lead Zirconate-Titanate (PZT), it creates a strain or deformation in the piezoelectric material. Due to this strain, it creates an electrical potential difference, a voltage. Fig. 11 shows piezoelectric pressure sensors

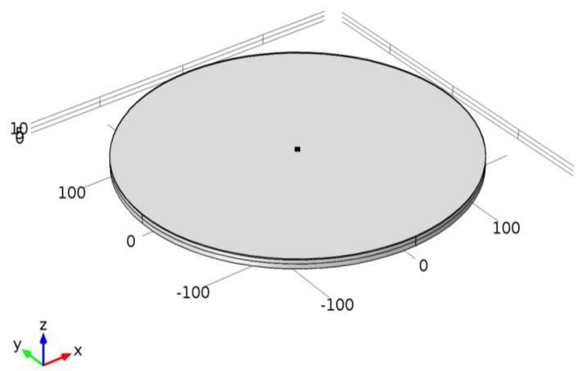

Figure 11 Piezoelectric pressure sensor

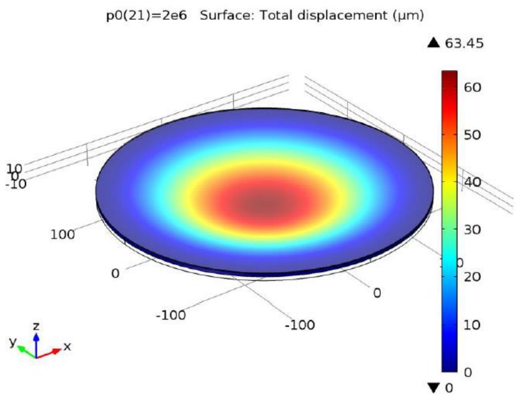

Figure 12 The model of piezoelectric pressure sensor

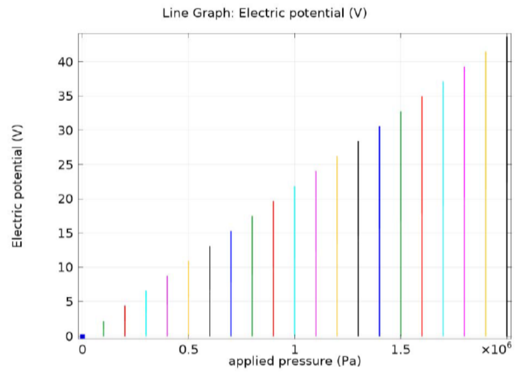

Figure 13 Graph of Applied pressure (Pa) Vs Electric potential (V)

Capacitive Pressure Sensor

A capacitor is composed by two conductive plates, which can store an electric charge. Then potential difference occurs across two conductive plate of capacitor which may be maintained by external voltage. A capacitive pressure sensor measures a pressure by detecting change in electrostatic capacitance; at least one electrode of the capacitor is on a moving plate (S.P. Chang *et al*, 2004; M. Shahiri *et al*, 2012). The advantage of capacitive sensors over the piezoresistive type is that they consume less power, whereas they have a nonlinear output signal and are more sensitive to electromagnetic interference. Capacitive sensors are suitable with most mechanical structures, and they have high sensitivity and low temperature drift. Figure.14 shows capacitive pressure sensors.

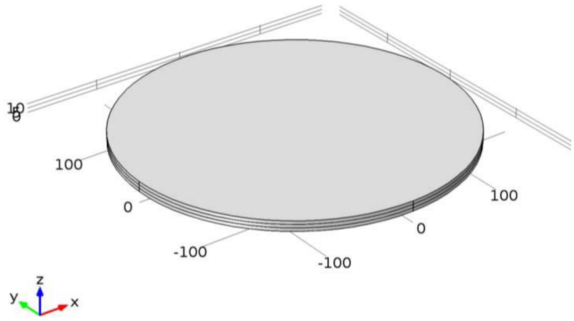

Figure 14 Capacitive pressure sensor

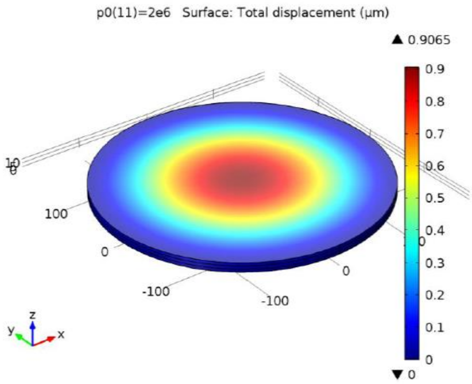

Figure 15 The model of capacitive pressure sensor

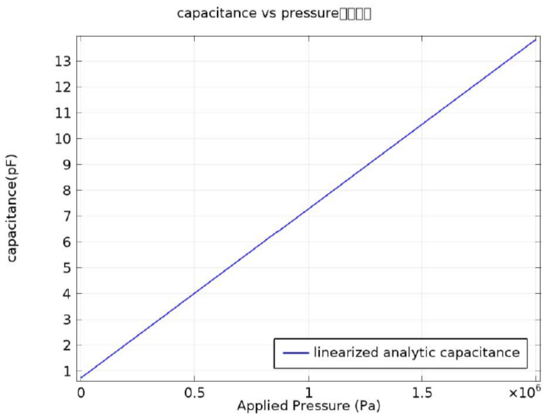

Figure 16 Graph of Applied pressure (Pa) Vs Capacitance (pF)

Conclusion

Modeling and simulation of capacitive, piezoelectric and piezoresistive pressure sensors using COMSOL Multiphysics. By observing the outputs we conclude that the piezoelectric pressure sensor is advantageous as it shows the maximum displacement, therefore it have the high sensitivity. The fabrication of capacitive pressure sensor is simple and has the low cost with highest accuracy as compared to piezoelectric and piezoresistive pressure sensor.

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