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Characteristic and analysis of silicon germanium material as MEMS pressure sensor

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ABSTRACT

The silicon based pressure sensor is one of the major applications of the piezoresistive sensor. This paper focuses on the structural design and optimization of the MEMS piezoresistive pressure sensor to enhance the sensitivity. A finite element method (FEM) is adopted for designing the performance of a silicon based piezoresistive pressure sensor. Thermal as well as pressure loading on the sensor is applied to make a simulation results. In order to achieve better sensor performance, a parametric analysis is performed to evaluate the system output sensitivity of the pressure sensor. The design parameters of the pressure sensor include the location of piezoresistors and the new structural material used for designing of the piezoresistors in the membrane is poly-Silicon Germanium in which germanium is about 60%. The findings depict that proper selection of the piezoresistors location and the new structural material of the piezoresistors in the membrane can enhance the sensor sensitivity.

Keywords: Piezoresistors, sensor, parametric analysis, silicon germanium, piezoresistivity, sensitivity

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INTRODUCTION

The silicon based pressure sensor is one of the major applications of the piezoresistive sensor. Nowadays, silicon piezoresistive pressure sensor is a matured technology in industry and its measurement accuracy is more rigorous in many advanced applications. The fundamental concept of piezoresistive effect is the change in receptivity of a material resulting from an applied stress. This effect in silicon material was first discovered by Smith, C.S.[1] in the 1950's and was applied extensively in mechanical signal measurement for years. Smith proposed the change in conductivity under stress in bulk n-type material and designed an experiment to measure the longitudinal as well as transverse piezoresistance coefficients. Pfann, W.G., and Thurston,R.N.[2] presented the shear piezoresistance effect, designed several types of semiconductor stress gauges to measure the longitudinal, transverse, shear stress and torque, and employed a Wheatstone bridge type gauge in mechanical signal measurement.

Piezoresistance coefficient is a function of impurity concentration and temperature. Hence the thermal effect will influence the measurement result of a piezoresistive sensor. Kanda.Y [3] produced a piezoresistance coefficient study about orientations, impurity concentration and temperature. Lund,E., and Finstad,T [4] also studied the temperature dependence of piezoresistance coefficient by four points bending experiment. The piezoresistive effect on polysilicon is another method to apply for mechanical signal sensing, French,P.J.[5] presented the piezoresistive effect in polysilicon and its applications to strain gauges. In French's study, a comparison is made between theory and experiment for longitudinal and transverse strain measurements of n-type and p-type materials. Piezoresistive pressure sensor design is widely studied at 1990's in MEMS and electronic packaging field. Jaeger [6] employed piezoresistive sensor made on silicon chip to measure the stresses within electronic packaging devices. Kanda[7] applied MEMS process to fabricate piezoresistive pressure sensors on {100} and {110} wafer for optimum design considerations. Recently, the finite element method (FEM) is widely adopted for stress prediction, thermal effect reduction, packaging design and reliability enhancement of piezoresistive sensor.

In this paper, the Finite element analysis demonstrated a promising result for prediction of sensor performance. The Finite element analysis is adopted to optimize the sensor design. The design parameters of the pressure sensor include a new material for designing piezoresistors, piezoresistors arrangement pattern and to place the piezoresistors on the diaphragm.

PIEZORESISTIVE PRESSURE SENSOR

The pressure sensor is a device, which can be used to measure static pressure or a pressure in moving fluids [8].There are three types of pressure measurements: (1) Absolute pressure, (2) Differential pressure and (3) Gauge pressure. Piezoresistivity is a common sensing principle for micromachined sensor. The choice of the piezoresistive transducer element was purely guided by the specific application needed. Piezoresistive sensing method utilizes piezoresistors where these resistors are varied through external pressure, in order to measure the physical parameters such as pressure, force and flow rate. The sensor needs to withstand the pressure that was intended to be measured and at the same time provide an accurate value of the pressure. A piezoresistive pressure sensor consists of a thin monocrystaline silicon membrane supported by a thick silicon rim as shown in Figure 1. The diaphragm is fabricated by etching away the bulk silicon on a defined region until a required thickness is reached. Piezoresistors are made by diffusing or implanting into the membrane typically close to the edges. The diaphragm of the pressure senor acts like a mechanical stress amplifier. The silicon is not only used as a substrate for the diffused resistors but also as an elastic material [9].

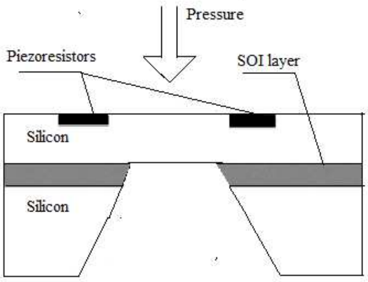

Figure 1.Pressure Sensor

When a pressure difference is applied across the device, the thin diaphragm will bend downward or upward, indicating traction or compression on the piezoresistors. The resistance change caused by this stress can be easily measured. The latest piezoresistive pressure sensors are up to ten times more sensitive than old transducers and with response times as rapid as a millisecond. These sensors are used for applications as automotive, hi-fi, aerospace and medical equipment industries. More than a dozen applications for pressure sensors have been identified and silicon thin-diaphragm piezoresistive sensors are responsible for many of these systems needs. These sensors are used in vehicles to control the ignition and the composition of the petrol mixture, in audio systems to compensate for loudspeaker resonance and in medical for dialysis, middle ear diagnosis, and disposable blood pressure meters [9].

EXPERIMENTAL SECTION

Silicon wafer (100) covered with SiO_2 were used as the starting material. The poly-Silicon Germanium layer has been deposited using chemical vapor deposit. The film was doped through ion implantation of boron with dosages between $2\text{-}10^{3\ \text{to}}$ $4\text{-}10^{3}cm^{-2}$.The resistors are created by etching the poly-Silicon Germanium. From Figure 2. we can observe that the resistivity of poly-Silicon Germanium reduces with increasing boron concentration . In boron doped poly-Silicon Germanium films, the decreased resistance with increasing Germanium fraction is due both to the increased effective carrier concentration and the higher Hall mobility as given by Bang et al,[10]. To study the temperature coefficient of resistance (TCR) of the layers, four point resistance measurements of patterned structures with different lengths (from 0.5 to 3 mm) and widths (from 25 to 150 mm) have been performed in the temperature range of 25 to 150^{o}C. The relative resistance change with temperature for poly-Silicon Germanium is shown in Figure 3. with the doping concentration as the varying parameter. The resistivity of a polycrystalline material is determined by the resistance within the grains and the “barrier” resistivity across the grain boundaries, which is controlled by a thermionic emission process given by Jiang et al[11]. At a very low and moderate doping concentration level the effect of the grain boundaries would be dominant. This lead to a non-linearity (as expected from the thermionic emission model) and gives a performance related to negative temperature coefficient of resistance. At high temperature the grain boundary resistance decreases as more and more carriers are available to cross the boundary.

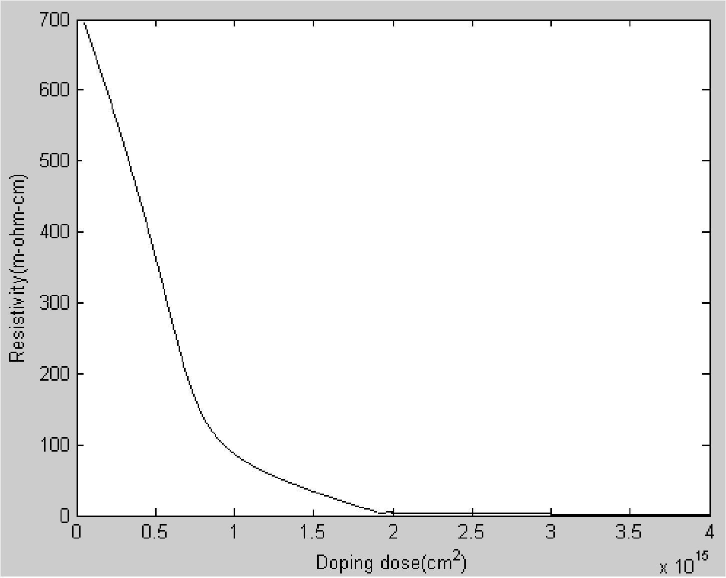

Figure 2.Resistivity versus doping concentration

At higher doping levels the barrier height is small and the effect of the grain boundaries is negligible compared to the resistivity of the grains. Within the grains the current transport is by carrier drift, resulting in a positive TCR [12] as the mobility decreases with temperature (thermal scattering), and the resistivity of the grain region increases.

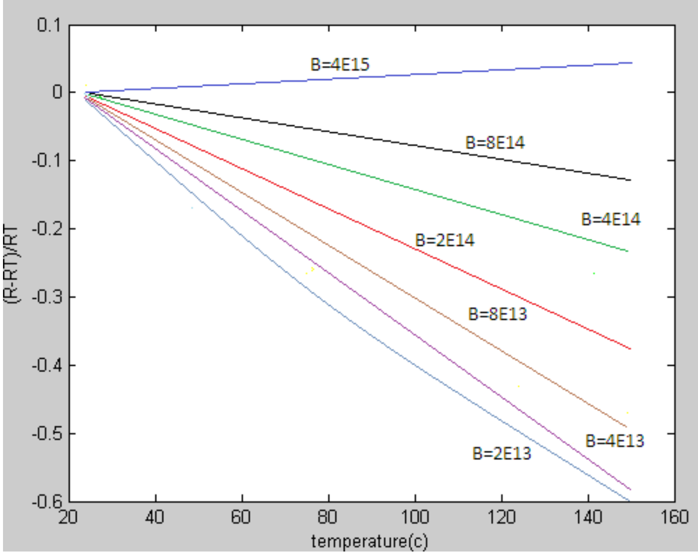

Figure 3. Dependence of resistivity on temperature for poly-Silicon Germanium

DETERMINATION OF PIEZORESISTIVITY

The finite element simulations were performed as given by Gonzalez et al[13] to find the value of stress induced in the piezoresistors placed on the diaphragm of the pressure sensor. The Young's modulus is assumed to be 146GPa (for Germanium 60%).The value is based on the weighted average values of poly-Silicon and poly-Germanium given by Franke et al[14].Finite element simulation is carried out to find the resistance change and the value of stress induced in the diaphragm. The values were substituted in the equation (1) given by Leci [15] and the piezoresistive coefficient were calculated.

$$\frac{\Delta R}{R} = \sigma\left(\pi_l \cos^2\varphi + \pi_t \sin^2\varphi - \pi_{lt}\cos\varphi\sin\varphi\right) \tag{1}$$

Table 1 shows the obtained longitudinal and transversal piezoresistive coefficients for the different materials such as poly-Silicon Germanium, monocrystalline Silicon Germanium, poly Silicon, Silicon and strained Silicon. Poly-

Silicon Germanium with 60% Germanium showed slightly better piezoresistive properties than poly-Silicon, although at high doping levels the piezoresistivity of poly-Silicon Germanium seems to be practically independent on Germanium content.

Table 1. Piezoresistive coefficients values for different materials

Co-efficient10^{11}[Pa^{-1}]	Poly-$SiGe_{60}$	Mono-SiGe	Poly-Si	Si[110]	$Si_{0.1}Ge_{0.9}$[110]
Π_l	+13	+4.25	+53.1	+56	+76
Π_t	+0.9	+0.125	-18.1	-48	-60

PARAMETRIC STUDY FOR SENSOR SENSITIVITY

A piezoresistive pressure sensor is studied as a first possible application of piezoresistors which was made of polycrystalline silicon germanium in which the germanium content is 60%.The device consists of a thin square poly-Silicon Germanium membrane with four poly-Silicon Germanium piezoresistors placed on top in a Wheatstone bridge configuration as shown in Figure 4.

When pressure is applied to the diaphragm of the pressure sensor, the diaphragm deflects creating a change in resistance in the piezoresistors. The piezoresistors are connected as a Wheatstone bridge. The four piezoresistors in the Wheatstone bridge are assumed to be ideally balanced ($R_2/R_4=R_3/R_1$) under zero-pressure. Thus, the bridge output voltage is zero in a zero-pressure condition. When pressure is applied to the diaphragm, the membrane will deform and induce bending stress, which changes the resistance in the wheatstone bridge circuit due to the piezoresistive effect.

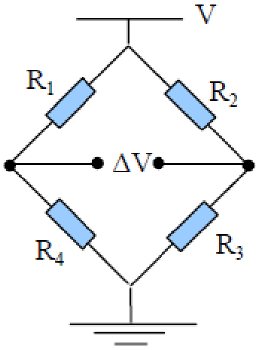

Figure 4. Wheatstone bridge configuration of the four piezoresistor

The piezoresistive coefficients can be related to the fractional change in resistance to the applied stress and is given by the formula:

$$\frac{\Delta R}{R}=\pi_l\,\sigma_l+\pi_t\,\sigma_t \tag{2}$$

Where π_l and π_t are the longitudinal and transverse piezoresistive coefficients, while σ_l and σ_t represent the longitudinal and transverse stress components. The resistance changes translate into a variation in the output voltage of the bridge as shown by the expression

$$\frac{\Delta V}{V}=\frac{r}{(1+r)^2}\left(\frac{\Delta R_1}{R_1}-\frac{\Delta R_2}{R_2}+\frac{\Delta R_3}{R_3}-\frac{\Delta R_4}{R_4}\right) \tag{3}$$

Where r is given by

$$r=\frac{R_2}{R_1}=\frac{R_3}{R_4} \tag{4}$$

The finite element analysis is employed to analyze the sensor sensitivity and stability of the piezoresistive pressure sensor. In the parametric investigation, the possible five location of piezoresistors in the square diaphragm, and the material of the membrane were considered. The piezoresistors were laid on the diaphragm in five different positions as illustrated in Figure 5. The diaphragms were subjected to pressure and the parametric study results are indicated as follows:

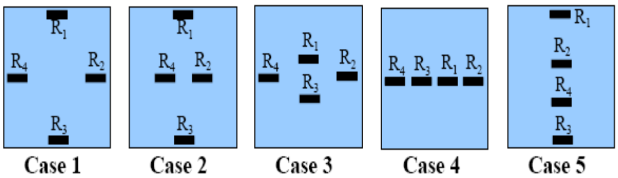

Figure 5.The five location of piezoresistors

Due to the positive transversal piezoresistive coefficient (π_t), it is best to place the transversal piezoresistors in the centre of the membrane where the stress is negative instead of on the edge. From the parametric study it was found that case 3 is the best suitable position to place the poly-Silicon Germanium piezoresistors on the diaphragm. The piezoresistors placed on the diaphragm of the pressure sensor as in case 3 gives a sensitivity of about 39 mV/V/bar and it was found that the best material for piezoresistors was poly-Silicon Germanium.

CONCLUSION

The piezoresistive properties of poly-Silicon Germanium with 60% Germanium were studied as a function of doping concentration and resistivity. This poly-Silicon Germanium film has a low temperature coefficient of resistance, which is ideal for piezoresistive sensors. The optimum positions of the poly-Silicon Germanium piezoresistors were found to be towards the center and sides of the square diaphragm. The simulation work showed that, a pressure sensor with poly-Silicon Germanium as the piezoresistive material gave a maximum sensitivity of 39 mV/V/bar.

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