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A novel temperature compensated piezoresistive pressure sensor

M. Aryafar, M. Hamedi, M.M. Ganjeh *

Mechanical Engineering Department, University of Tehran, Tehran, Iran

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ABSTRACT

The main drawback of current piezoresistive pressure sensors is the drop of output voltage with increase in the operating temperature which severely reduces the measurement accuracy. This paper presents a novel passive technique for temperature compensation of silicon piezoresistive pressure sensors. The built-in compensation technique eliminates the need for expensive and time consuming calibration process required for each sensor inside a fabricated batch. In this technique, extra polysilicon resistors with negative Temperature Coefficient of Resistivity (TCR) are employed for compensation purpose. Through applying this technique, Temperature Coefficient of Sensitivity (TCS) of the conventional non-compensated sensor was reduced to zero. Analytically derived equations and verified Finite Element Model considering mechanical, piezoresistive and electrical characteristics of the sensor are adapted to analyze the behavior of the sensor. The implementation of the introduced technique is compatible with conventional MEMS devices fabrication process. The compensated sensor is advantageous for pressure measurement in harsh environments with temperature variations.

1. Introduction

Silicon PiezoResistive Pressure (SPRP) sensors are one of the best studied and commercialized devices among all MEMS devices due to their simple and small structure, easy reading circuit, batch fabrication capability and low price [1]. Among diverse applications of the SPRP sensors, there are environments in which the temperature increases as high as 150 °C while consistent performance and accuracy from the sensor is expected [2]. However, in such situations, the piezoresistive coefficient of silicon reduces which leads to the fluctuations in the output voltage of the SPRP sensor. This will adversely affect the precision of the sensor [3].

It is well understood that electrical resistance of single crystalline silicon increases as temperature rises while its piezoresistive coefficient decreases [4]. Temperature-cross sensitivity of SPRP sensor consists of a temperature coefficient of offset (TCO) and sensitivity (TCS). The former arises from mismatch of resistors value and residual stress on membrane or packaging effects. On the other hand, the main cause of the latter is negative temperature coefficient of piezoresistive coefficient (TCΠ).

The efforts made to overcome this undesired effect include passive and active approaches. Passive methods mainly utilize extra resistors in full bridge or half-bridge arrangements. Canceling out TCO and TCS are typically achieved through utilizing trimmed parallel resistors and a temperature dependent series resistor [5]. On the other hand, in active methods, TCO and TCS is compensated using information received from an additional temperature sensor incorporated into the sensor chip [6]. Totally, active methods require extensive temperature and pressure

* Corresponding author. Tel.: +98 9128882459; fax: +98 2166379118.
E-mail addresses: m.aryafar@ut.ac.ir (M. Aryafar), mhamedi@ut.ac.ir (M. Hamedi), maghsoudi.mo@ut.ac.ir (M.M. Ganjeh).

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calibration which are time consuming and expensive operations. In order to compensate TCS, Bruyker and Puers [7] introduced a thermostatic control concept in which the temperature of sensor is held constant during the operation. Quo et al. [8] implemented the digitized curve fitting technique in SOI pressure sensor to compensate across a wide range of temperature. Futane et al. [9] used ANN based CMOS ASIC design to improve the temperature-drift compensation of the sensor.

Despite all of the published efforts, the fluctuation of output voltage against variation in ambient temperature is still a persistent factor undermining the precision of SPRP sensors. The present study discusses utilization of extra polysilicon resistors located outside the edge of the sensor diaphragm, in serial configuration with piezoresistor elements. Therefore, the extra resistors will not experience any pressure induced stress. The TCR of polysilicon can be adjusted to negative, zero, or positive values by the changing the doping concentration. The TCR of polysilicon resistors in low doping concentrations (less than $10^{15}\,\text{cm}^{-3}$) is negative which causes drop in their resistance as temperature increases [10,11]. This resistance drop of polysilicon resistors will increase the voltage of piezoresistors and compensate the TCS of the sensor. To assess the sensor performance, Finite Element Model is developed.

This technique is an embedded passive technique which is compatible with batch fabrication of the sensor. It only requires the conventional process of deposition and doping of polysilicon on Si wafer which is also possible to combine these two processes into an in-situ polysilicon doping process. In contrast to active methods, this technique does not need any complex external circuit and calibration of each fabricated sensor. Furthermore, existing passive techniques demand constant current supply while our technique works with constant voltage supply which is more simpler and cost-effective.

2. Sensor design

Conventional non-compensated SPRP sensor consists a thin square diaphragm of side $2a$ and thickness h which undergoes upward deformation under the applied pressure P. Piezoresistor elements are located on high stress regions of membrane and their electrical resistance change due to pressure-induced stress. Piezoresistors are connected together in a Wheatstone bridge configuration as read-out circuit. Four p-type piezoresistors oriented in $\langle 110\rangle$ direction and arranged as is shown in Fig. 1 constitute the sensor.

Output voltage V_o of the sensor in response to applied pressure is given as:

$$\frac{V_o}{V_{in}} = \frac{\Delta R}{R} = \Pi\left(\frac{a}{h}\right)^2(1-\upsilon)P \tag{1}$$

It can be seen that the output voltage largely depends on piezoresistive coefficient of the piezoresistors, Π.

Temperature Coefficient of Sensitivity of the sensor (TCS) is defined as:

$$\text{TCS} = \frac{1}{S}\frac{\partial S}{\partial T} \tag{2}$$

In order to compensate TCS of the sensor, four identical polysilicon resistors are employed in configuration depicted in Fig. 2. The initial resistance of polysilicon resistors and piezoresistors are considered R' and R respectively where $\frac{R'}{R} = K$. If temperature rises, resistance of polysilicon resistors decreases due to its negative TCR. Since piezoresistors and polysilicon resistors are arranged in a serial configuration (current is the same through each resistor), the voltage of piezoresistors V_{in} will increase. Consequently, V_o of the sensor remains consistent in contrast to non-compensated sensor. This means TCS of the sensor is compensated. The parameters of the compensated sensor is defined in Table 1.

3. Analytical model

In order to develop the governing equations of the compensated sensor, we start by expressing the resistance of each piezoresistor at operating temperature T_f and external pressure of P as:

$$R^{(P,T_f)} = R_0 + R_0(\alpha\Delta T) \pm R_0\left[(\Pi_0 + \beta\Delta T\Pi_0)P\left(\frac{a}{h}\right)^2(1-\upsilon)\right] \tag{3}$$

The term $R_0(\alpha\Delta T)$ refers to the TCR, but the last term represents the piezoresistive effect. The positive sign is used for R_1 and R_3 where negative sign is used for R_2 and R_4.

Since the polysilicon resistors are located outside of diaphragm, they will not experiences any pressure-induced

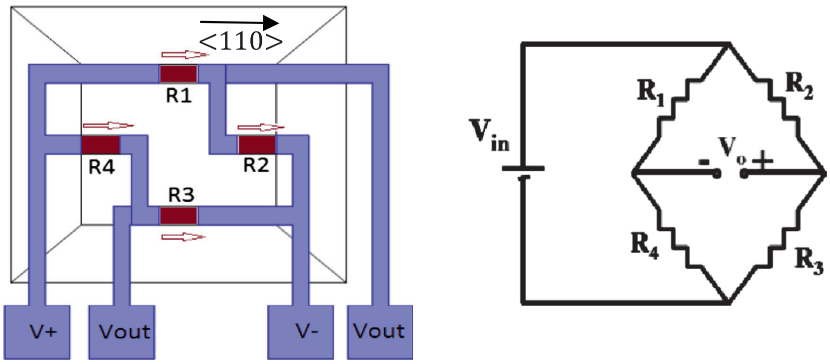

Fig. 1. Configuration of conventional non-compensated sensor.