IARJSET

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Vol. 6, Issue 10, October 2019

# MOS integrated high sensitivity MEMS Piezoresistive pressure sensor without Wheatstone Bridge

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**Abstract:** Wheatstone bridge circuit is generally employed in Piezoresistive pressure sensor having four piezoresistors used to convert the magnitude of the applied pressure into a proportional change in resistance. Linear relationship between the applied pressure and the change in resistance is possible in piezoresistive pressure sensors. The differential voltage obtained from the Wheatstone bridge circuit is further amplified using signal conditioning circuit to realize large voltage sensitivity. The recent trend in industrial applications prefers a current output from the pressure sensors for transmission to the control room from the remote sensing location. The current practice is to convert the voltage obtained from differential amplifier into a proportional current in the piezoresistive pressure sensors. In this work, the authors introduce a simple technique that directly converts change in piezoresistance into a current using MOSFET current amplifiers. MOS integrated pressure sensor is introduced, since it is possible to integrate MOSFETs in silicon using Micro Electro Mechanical Systems so that the piezsoresistive mechanism and current transmitter can be integrated in a single chip.

**Keywords:** Micro electro mechanical systems; Metal oxide semiconductor field effect transistor; Piezoresistor; Sensitivity; IntelliSuite; pSPICE.

## I. INTRODUCTION

Miniaturization of technology has been possible due to advances in MEMS devices, specifically in micro sensors and actuators. Pressure sensing using micro structures has been the first invention of MEMS technology and has almost matured. Pressure sensors are widely used in automotive, aerospace, industrial, and medical applications. Several pressure sensors using MEMS technology have been proposed with capacitive, piezoresistive and optical detection [1-4]. Capacitive pressure sensors have very low dynamic range which usually requires sophisticated interfacing circuit to get an appreciable output. Piezoresistive detection technique is more favorable than capacitive detection in MEMS because of better scaling characteristics [5]. In MEMS pressure sensors, the diaphragm of the sensor will deform when a pressure difference is applied and induce bending stresses which contributes to resistance change in piezoresistors embedded on the SOI (Silicon-On-Insulator) diaphragm [6]. Methods of improving sensing accuracy and reliability while optimizing the dimensions of diaphragm and piezoresistors has been constantly investigated [7-11]. Piezoresistive pressure sensor generally employs a Wheatstone bridge comprising four piezoresistors to convert the pressure into a proportional voltage. These sensors are preferred due to the excellent linearity that can be achieved with piezoresistive pressure sensors. The differential voltage obtained from the Wheatstone bridge circuit is further amplified to realize large voltage sensitivity. However, industrial applications prefer a current output from the MEMS sensors for transmission to the control room from the remote sensing location. The recent trend is to convert the voltage obtained from differential amplifier to a proportional current in the piezoresistive pressure sensors. In this work, the authors introduce a simple technique that directly converts change in piezoresistance into a current using MOSFET current amplifiers. Since, it is possible to integrate MOSFETs in silicon MEMS, the piezsoresistive mechanism and current transmitter can be integrated in a single chip.

## II. STRUCTURE OF MEMS PIEZORESISTIVE SOI PRESSURE TRANSMITTER

SOI technology provides greater advantage in micromachined devices. The typical structure of MEMS piezoresistive SOI pressure transmitter considered in this analysis is shown in Fig. 1. It is a planar silicon diaphragm formed by anisotropic etching (bulk micromachining). The silicon diaphragm of the pressure transmitter is sandwiched inbetween the insulator layers of $SiO_2$. The buried $SiO_2$ layer isolates the diaphragm electrically from the substrate and also it acts

DOI 10.17148/IARJSET.2019.61009

as the etch stop layer during the pressure port realization by wet etching from back side. The top $SiO_2$ layer provides electrical isolation between the piezoresistors realized on the diaphragm. The silicon substrate at the bottom of the diaphragm provides mechanical support. It is etched partially from bottom up approach so that a square cavity is formed at the bottom of the pressure transmitter as shown in Fig.1. This cavity acts as a pressure port.

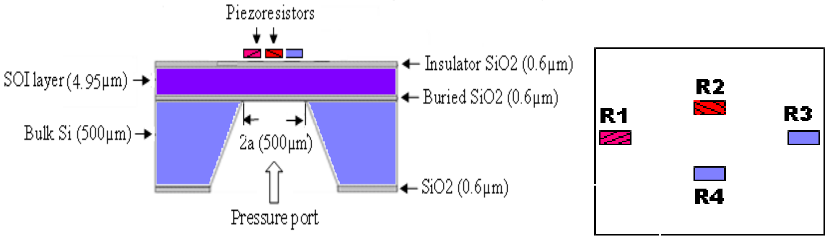

Fig.1. Structure of MEMS piezoresistive SOI pressure sensor.

Piezoresistors with different piezoresistive properties can be easily fabricated on the top of the silicon diaphragm by surface micromachining techniques. Polycrystalline silicon has acceptable piezoresistive properties and it is possible to achieve zero temperature coefficient of resistance by adjusting doping. Also, it is very simple to realize the resistors using surface micromachining on the oxidized silicon diaphragm.

## III. PROPOSED MOS INTEGRATED PRESSURE SENSOR

In the present MOS integrated pressure transmitter, there are two piezoresistors embedded in the pressure sensing silicon diaphragm. The first resistor (R1) is placed at the left edge and the second one (R2) is placed closer to the centre of the diaphragm as shown in Fig.(1). The resistor R1 experiences compressive stress and the resistor R2 experiences tensile stress when the pressure is applied at the bottom side pressure port as shown in Fig.(1). Therefore, R1 shows a decrement in its value and R2 exhibits a increment in its resistance with increasing pressure. These two resistors form the reference resistors for the current mirrors formed by NMOSFETs (M1, M2, M3 and M4) of MOS integrated pressure sensor proposed in this work as shown in Fig.2.

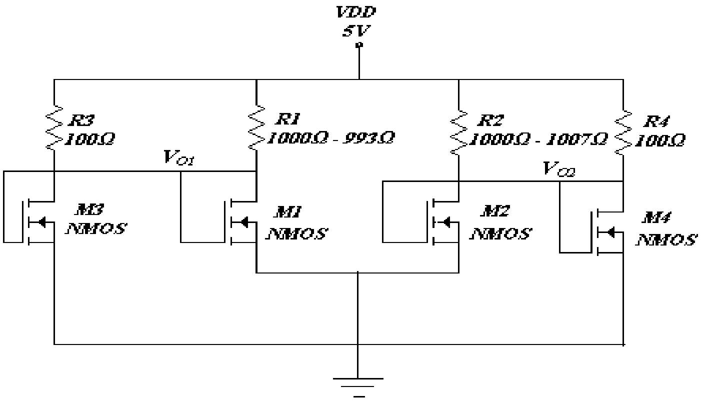

Fig.2. MOS integrated pressure sensor.

The resistor R1 acts as the reference resistor in the NMOS (M1) current mirror and the R2 acts as the reference resistor in the NMOS (M2) current mirror. When the applied pressure is null, the resistors R1 and R2 are equal to the designed value of 1000Ω. Therefore, the magnitude of the drain current ($I_{n1}$) of NMOS (M1) is equal to the drain current ($I_{n2}$) of NMOS (M2) if both NMOS M1 and M2 are matched perfectly. When the pressure increases the R1 decreases by a value of $\Delta R$ and R2 increases by a value of $\Delta R$, $I_{n1}$ (M1) increases and $I_{n2}$ (M2) decreases by a value of $\Delta I$. This $\Delta I$ is further amplified by the current amplifiers and resulting in a large differential voltage set at terminals $V_{O1}$ and $V_{O2}$.

### *3.1. Background theory*

The drain current $I_{n1}$ and $I_{n2}$ of NMOS (M1 and M2) can be written as

$$I_{n1} = \mu_n C_{oxn}\frac{W_1}{L_1}(V_{GS1} - V_{T1})^2 \tag{1}$$

$$I_{n2} = \mu_n C_{oxn}\frac{W_2}{L_2}(V_{GS2} - V_{T2})^2 \tag{2}$$

where

$\mu_n$ is the mobility of electron charge carriers, $C_{oxn}$ is the oxide capacitance, $W_1$ and $W_2$ are the channel widths, $L_1$ and $L_2$ are the channel lengths, $V_{GS1}$ and $V_{GS2}$ are the gate to source voltages, $V_{T1}$ and $V_{T2}$ are the threshold voltages of NMOS M1 and M2 respectively since the MOSFETs are operated in the saturated region.

When the pressure is zero, both $I_{n1}$ and $I_{n2}$ are equal since $\frac{W_1}{L_1} = \frac{W_2}{L_2}$ and these two transistors M1 and M2 are matched pair.

But when the pressure increases, R1 decreases by $\Delta R$ .

$$I_n = \frac{V_{DD} - V_{GSn}}{R1 - \Delta R} \tag{3}$$

From Eqns.1 and 4, a quadratic equation for $V_{GSn}$ can be formed as follows:

$$\frac{K_n}{2}V_{GSn}^2 + V_{GSn}\left[\frac{1}{R1-\Delta R} - V_{Tn}K_n\right] + \left[V_{Tn}^2\frac{K_n}{2} - \frac{V_{DD}}{R1-\Delta R}\right] = 0 \tag{4}$$

Solving Eqn. (4)

$$V_{GSn} = \frac{\left[V_{Tn}K_n + \frac{1}{R1-\Delta R}\right] \pm \sqrt{\left[(-V_{Tn}K_n + \frac{1}{R1-\Delta R})\right]^2 - 2K_n\left[-\frac{V_{DD}}{R1-\Delta R} + V_{Tn}^2\frac{K_n}{2}\right]}}{K_n} \tag{5}$$

When R1 decreases, $V_{GSn}$ would increase and therefore the NMOS drain current $I_{n1}$ (M1) increases. In a similar fashion, R2 increases by $\Delta R$ thus decreasing the $|V_{GS2}|$ and hence the NMOS drain current $I_{n2}$ (M2) decreases by the same amount as $I_{n1}$. If the change in $V_{GSn}$ is referred as $\Delta V_{GSn}$ due to the change in resistance $\Delta R$ in both R1 and R2 on application of pressure, the new $I_{n1}$ and $I_{n2}$ will be

$$I_{n1} = \frac{1}{2}k_n\left[\left(V_{GS1} + \Delta V_{GS1}\right) - V_{T1}\right]^2 \tag{6}$$

where $k_n = \mu_n C_{oxn}\frac{W_1}{L_1}$ and

$$I_{n2} = \frac{1}{2}k_n\left[\left(V_{GS2} - \Delta V_{GS2}\right) - V_{T2}\right]^2 \tag{7}$$

So, $V_{O1} = V_{CC} - I_{n3}R_3$ similarly

$V_{O2} = V_{CC} - I_{n4}R_4$

When pressure is zero, $I_{n3} = I_{n4}$ and therefore $\Delta V = 0$. With increase in pressure $I_{n1}$ increases and $I_{n2}$ decreases. Therefore $\Delta V = V_{O1} - V_{O2}$ will increase and this differential voltage $V_{O1} - V_{O2}$ is directly proportional to the applied pressure.

## IV. PERFORMANCE ANALYSIS

Having explained the theoretical aspects of the proposed piezoresistive pressure transmitter, this section describes the design of the same. pSPICE simulation has been used for the circuit analysis and the design.

### *4.1. Extraction of transconductance coefficient ( $k_n$) and threshold voltage ($V_{Tn}$) of the MOSFET*

The authors intend to design the circuit using NMOS that are already available in the pSPICE library. The transconductance coefficient $(k_n)$ and the threshold voltage $(V_{Tn})$ are extracted from the transfer characteristics obtained at $V_{DS}$ = 50 mV. The drain current in the linear region of the MOSFET operation is given by

$$I_D = \mu C_{ox}\frac{W}{L}(V_{GS} - V_T - \frac{V_{DS}}{2})V_{DS} \tag{8}$$

$$I_D = K(V_{GS} - V_T - \frac{V_{DS}}{2})V_{DS} \tag{9}$$

The transconductance in the linear region can be written as

$$g_{m(linear)} = \frac{dI_D}{dV_{GS}} = KV_{DS} \tag{10}$$

Hence, the transfer characteristics of these transistors are obtained by setting the $V_{DS}$ at 50 mV for both NMOS. The threshold voltage $(V_{Tn})$ is obtained by linear extrapolation method and the transconductance coefficient $(k_n)$ is estimated from the $g_{m(linear)}$ values obtained from the slope of the $I_D–V_{GS}$ characteristics as shown in Fig.3. The values thus obtained are summarized in Table 1. These two transistors would operate in the places of M1 and M2 with W/L ratio of 100µm/20µm as shown in Fig. (2).

Table 1. Extracted $(k_n)$ and $(V_{Tn})$ parameters of matched pair MOSFETs.

| DEVICE | $k_n\left(\frac{mA}{V^2}\right)$ | $V_{Tn}$ $(Volts)$ |
|---|---|---|
| NMOS | 0.5714 | 0.78 |

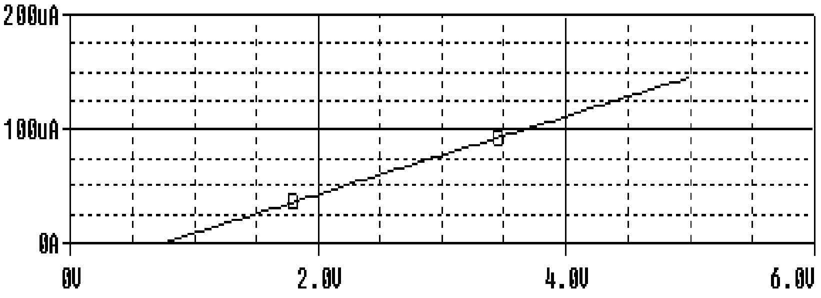

Fig.3. Estimation of threshold voltage of MOSFET.

### *4.2. Deflection and piezoresistive analysis*

In order to assess the performance of the pressure transmitter, it is necessary to estimate the change in resistance in the piezoresistors embedded on the diaphragm of the pressure sensor. The structure shown in Fig.(1) has been created and simulated using IntelliSuite MEMS design tool. The dimension of the diaphragm has been designed to achieve maximum deflection sensitivity using burst pressure incorporated design reported in the reference [9]. Silicon piezoresistors have also been embedded in the diaphragm for piezoresistive analysis. The dimensions of silicon diaphragm and piezoresistors are summarized in Table 2 as seen in the references [9, 11].

Table 2. Dimensions of silicon diaphragm and piezoresistors.

| Area of the diaphragm ($\mu m^2$) | Side length of the diaphragm (µm) | Thickness of the diaphragm (µm) | Length of the resistors R1and R2 (µm) | Width of the resistors R1and R2 (µm) | Thickness of the resistors R1and R2 (µm) |
|---|---|---|---|---|---|
| 500×500 | 500 | 4.95 | 100 | 20 | 0.6 |

The various constants used in the piezoresistive analysis are as follows: $\pi_{11} = 6.6\times10^{-5}$/MPa, $\pi_{12} = -1.1\times10^{-5}$/MPa and $\pi_{44} = 138.1\times10^{-5}$/MPa. The resistance under zero pressure condition has been fixed to be 1000 Ω. The measured piezoresistances (R1,R2) values with the applied pressure in the range of 0 to 0.1 MPa has been plotted as shown in Fig. 4.

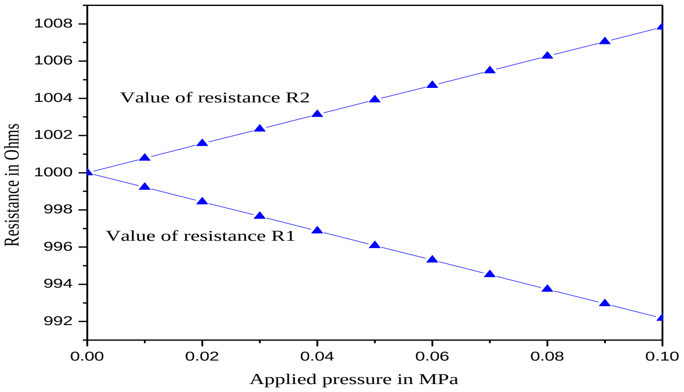

Fig.4. Measured value of piezoresistances (R1,R2) with the applied pressure.

## V. CONCLUSION

In this paper, a MOS integrated MEMS piezoresistive pressure transmitter has been introduced. The change in resistance of piezoresistor due to the pressure applied on the SOI diaphragm is converted into an appreciable current insitu by a MOSFET current mirror. It was shown that it is possible to produce a significant current that is proportional to the applied pressure. Further, it was demonstrated that a voltage signal is also obtained in the same circuit without a Wheatstone bridge and the voltage sensitivity can be appreciably increased by this arrangement. A differential current amplifier formed by NMOS and PMOS current mirrors along with two piezoresistors provides the current output. The current sensitivity of this sensor is estimated to be 4.017 mA/MPa at a load resistance of 0.5 Ω by simulation experiments using IntelliSuite and pSPICE softwares. Further, it is important to note that this pressure transmitter provides a differential output voltage that is proportional to the pressure with a voltage sensitivity of 55 mV/MPa. Since, MOSFET current mirrors are integrated insitu with the sensing elements, the benefits of silicon MEMS is fully reaped. Other major advantage of this proposed transmitter is its ability to give both current and differential voltage output insitu.

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