# Design and Analysis of a Novel MEMS Capacitive Ttire Pressure Sensor with High Sensitivity and Linearity

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**ABSTRACT:**
This paper is focused on a novel design of stepped diaphragm for MEMS capacitive pressure sensor used in tire pressure monitoring system. The structure of sensor diaphragm plays a key role for determining the sensitivity of the sensor and the non-linearity of the output. First the structures of two capacitive pressure sensors with clamped square flat diaphragms, with different thicknesses are investigated and their sensitivity and non-linearity are compared together. Finally for increasing the sensitivity and linearity, a new capacitive pressure sensor with a stepped diaphragm is introduced. A numerical solution for determination of the accurate sensitivity of the sensor is presented. The results show that the sensitivity of the sensor is increased from 0.063 fF/KPa with flat diaphragm to 0.107 fF/KPa with stepped diaphragm and also the non-linearity is decreased from 2.37% to 1.857%. In this design, the sensor sensitivity and output linearity are increased simultaneously.

**KEYWORDS:** Capacitive pressure sensor, sensitivity, tire pressure monitoring system, linearity.

## 1. INTRODUCTION

In recent years, significant progress has been carried out on Microelectromechanical systems (MEMS), in the meantime, pressure sensors have gained significant place in medical, automotive, industrial and aerospace industries due to various advantages like small size, low weight and compatibility. Automotive industries are the leading consumer of pressure sensors. Typical applications are Airbag or Tire Pressure Monitoring Systems (TPMS), Oil pressure sensing (OPS), Engine Management system (EMS), Vacuum brake booster and Transmission fluid pressure [1]. More and more countries are planning to announce the transportation rules that require vehicles installing the TPMS sensors for every wheel. To fulfill the market demand, recently the researches on TPMS sensors have been intensively motivated [2].

Maintaining correct inflation pressure in tires helps to keep vehicle handling and braking at its best, as well as improving fuel efficiency and tire life. In addition it can prevent such events as tread separations and tire blowouts which may cause loss of control of a vehicle and severe crashes such as rollovers [3]. A tire can lose up to half of its air pressure without appearing to be underinflated and most people ignore the state of their tires so data shows that nearly 250,000 accidents per year occur in the United States alone due to low tire pressure [4]. Tire pressure monitoring system (TPMS) is one of the biggest automotive safety equipment required for safety on the road. Tire pressure monitoring systems (TPMS) are a way of warning a driver that the tire is incorrectly inflated, which will decrease the safety and performance of the vehicle, and increase the risk of an accident [5]. The TPMS must illuminate a low tire pressure warning telltale not more than 20 minutes after the inflation pressure in one or more of the vehicle’s tires, up to a total of four tires, is equal to or less than either the pressure 25 percent below the vehicle manufacturer’s recommended cold inflation pressure [6].

In most of the direct TPM systems, MEMS pressure sensors are used. A Typical TPMS consists of a pressure sensor assembled with microcontrollers and an electronic circuit mounted inside the tire which continuously monitors the tire pressure and the information is sent to the driver whether the tire is correctly inflated or not [1]. The MEMS pressure sensors can either be piezoresistive or capacitive. MEMS capacitive sensors provide high pressure sensitivity, low noise, low power consumption and unlike piezoresistive sensors they have low temperature sensitivity, so they are more suitable for using in tire. The capacitor sensors suffer from the nonlinear output and low capacitance sensitivity [7]. To address these problems one can lessen the air gap and turn the diaphragm to the touch mode[8], [9] but in the beginning, when the pressure is low and the diaphragm has not yet turned into the touch mode, the output is nonlinear and has not so much sensitivity. One way to reduce the amount of non-linearity is to increase the diaphragm thickness [5]. It shall be noticed that by more increase in the diaphragm thickness, the sensor sensitivity will considerably decrease. Another way is to increase the middle part of the diaphragm. In this way the output characteristic will be more linear while the capacitor sensitivity decreases because of increasing the stiffness [10], [11].

In this paper, first capacitive sensor with clamped flat diaphragm is investigated and simulated as a main structure. For achieving more linear output, capacitive sensor with thicker diaphragm is used and to address the sensitivity problem we proposed capacitive pressure sensor with stepped diaphragm. Each sensor has a square diaphragm made of poly silicon material.

## 2. DESIGN OF MEMS CAPACITIVE PRESSURE SENSOR

The capacitive sensor is made of two parallel plates with air gap. With biasing DC voltage between two plates, they act as electrode of capacitors. The upper electrode is usually moving that can be square, rectangular or circular and the lower one is fixed. In these sensors the diaphragm moves, so the capacitance between two electrodes is changed and can be measured by an intermediate electronic circuit. The diaphragm's shape influences on deflection of the diaphragm due to the application of an external pressure. Among the variety of diaphragms, rectangular diaphragm has non-uniform stress distributions due to the lack of asymmetry of the structure [12] which resulted in the displacement of less than a square or circular diaphragm with the same areas [13]. With the same width, the effective areas for diaphragms of square and circular shapes are different. Under this condition, with the same pressure load, the square diaphragms have more center deflection than the circular diaphragms [14]. In addition a square diaphragm can easily and accurately be fabricated because of anisotropic nature of the silicon crystal structure [15]. As a result, it was decided to utilize a square diaphragm instead of a round structure. The structure of the sensor for clamped diaphragm consists of silicon back plate and poly silicon diaphragm.

In our design, the thickness of the 0.4 mm × 0.4 mm membrane is 5 µm, and the height of the air gap is about 5 µm. Fig. 1 illustrates the simulation setup of the capacitive pressure sensor with flat diaphragm. The residual stress for poly silicon is around 20 MPa. The Young's modulus and Poisson's ratio of poly silicon are assumed to be $160 \times 10^9$ Pa and 0.22, respectively. Poly silicon is used as the structural material for the sensor diaphragm because of low stress compared to other materials. High-temperature annealing of a low pressure chemical vapor deposition (LPCVD) of poly silicon thin film that is ion implanted with phosphorous can confine the residual stress as low as 20 MPa [15]. Two steps of improvement have been done to reduce the amount of non-linearity and increase the capacitor sensitivity of the sensor.

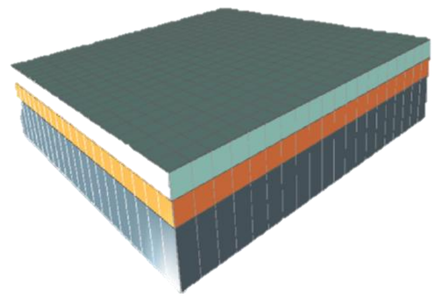


**Fig. 1**. Simulation setup of capacitive pressure sensor with flat diaphragm

Fig. 2 demonstrates the simulation setup of the capacitive pressure sensor with stepped diaphragm using Intellisuite® MEMS design tool. The stepped diaphragm could be applied to increase capacitive sensitivity. This structure is proposed with respect to the diaphragm deviation so that near the diaphragm center, the height of the air gap is about 5 µm and near the anchor the gap reduces to 2.5µm.

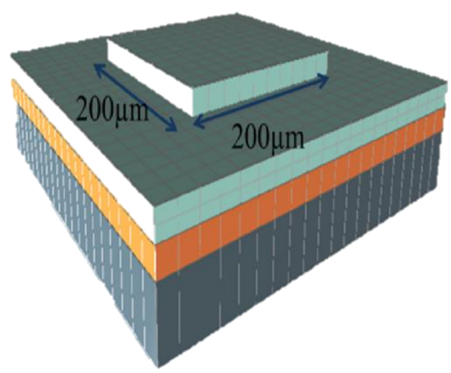



**Fig. 2**. Simulation setup of capacitive pressure sensor with stepped diaphragm

## 3. ANALYSIS OF CAPACITIVE PRESSURE SENSOR

Fig. 3 illustrates the cross-section view of the typical pressure sensor with flat diaphragm. The diaphragm side length is 2a, thickness h, the air gap is d and P is an external uniform pressure.

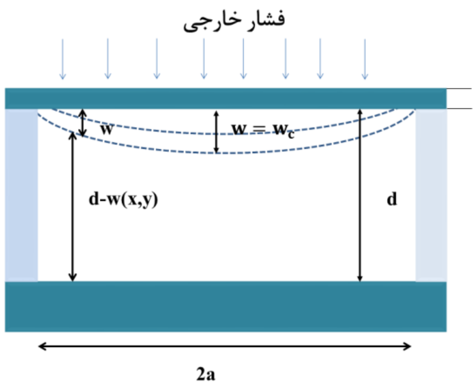



**Fig. 3**. Cross section view of typical pressure sensor with flat diaphragm

### 3.1. Mechanical Sensitivity Analysis

The central deflection, $w_c$, of a flat and circular diaphragm with clamped edges and with initial stress, due to a homogeneous pressure, P, can be calculated from [16]:

$$p = 5.33E\frac{h^4}{(1-v^2)R^4}\left(\frac{w_c}{h}\right) + 2.83E\frac{h^4}{(1-v^2)R^4}\left(\frac{w_c}{h}\right)^3 + 4\frac{h^2}{R^2}\left(\frac{w_c}{h}\right)\sigma \quad (1)$$

Where R is the radius, h is the thickness, E is young modulus, ν is the poison's ratio of the circular diaphragm, and $\sigma$ is residual stress. The deflection of a flat clamped square diaphragm without residual stress is given approximately by [17]:

$$p = 4.2E\frac{h^4}{(1-v^2)a^4}\left(\frac{w_c}{h}\right) + 1.58E\frac{h^4}{(1-v^2)a^4}\left(\frac{w_c}{h}\right)^3 \quad (2)$$

Where $a$ is the half-side length of the square diaphragm. For large value of initial tension, the deflection of a flat circular diaphragm can be represented by:

$$P = 4\frac{h^2}{R^2}\left(\frac{w_c}{h}\right)\sigma \quad (3)$$

The theory being valid for circular membranes is converted to the square diaphragms assuming equal areas $((2a)^2 = \pi R^2)$, thus by replacing $R^2$ with $4a^2/\pi$ in (3), the deflection of a flat square diaphragm can be approximated by [18]:

$$P = \pi\frac{h^2}{a^2}\left(\frac{w_c}{h}\right)\sigma \quad (4)$$

This resistance to bending due to initial stress can be added to (2) using the principle of superposition.

$$p = 4.2E\frac{h^4}{(1-v^2)a^4}\left(\frac{w_c}{h}\right) + 1.58E\frac{h^4}{(1-v^2)a^4}\left(\frac{w_c}{h}\right)^3 + \pi\frac{h^2}{a^2}\left(\frac{w_c}{h}\right)\sigma \quad (5)$$

With regard to the relationship between the center deflection and the applied pressure, it can be seen that if $(w_c / h)\langle\langle 1$ this relation is approximately linear.

The mechanical sensitivity of a diaphragm is defined as [19]:

$$S_M = \frac{dW}{dP} \quad (6)$$

Ignoring the third-order term, for a small deflection (less than 30 % of its thickness), the mechanical sensitivity of a flat square diaphragm can be determined by [20]:

$$S_M = \frac{a^2}{\pi h[4.2Eh^2/\pi a^2(1-v^2)+\sigma]} \quad (7)$$

### 3.2. Sensor Sensitivity Analysis

For square diaphragm small deflection at any point (x, y) can be determined via the following equation [21]:

$$W(x,y) = \frac{49P(x^2-a^2)^2(y^2-a^2)^2}{2304Da^4} \quad (8)$$

Where $a$ is the half side-length and the $D$ is called the flexural rigidity of the plate:

$$D = \frac{Eh^3}{12(1-v^2)} \quad (9)$$

The maximum deflection will be happen at the center (x=0, y=0) and it is derived as:

$$W_0 = \frac{49Pa^4}{2304D} \quad (10)$$

The capacitance for air as a dielectric is defined as [15]:

$$C = \iint \frac{\varepsilon}{d - W(x,y)}dxdy = \frac{\varepsilon}{d}\iint \frac{1}{1-\frac{W(x,y)}{d}}dxdy \quad (11)$$

Expansion Taylor series can be used for calculating the above integral. Taylor series expansion is given by the following equation:

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + \ldots \qquad for -1\langle x\langle 1 \quad (12)$$

Since in this case $(W/d)\langle 1$, therefore (12) simplified as follows:

$$C = \frac{\varepsilon}{d}\int_{-a}^{a}\int_{-a}^{a}\{1 + \frac{W(x,y)}{d} + \frac{W^2(x,y)}{d^2} + \ldots\}dxdy \quad (13)$$

As long as the sensor works in the small deflection, the capacitance, neglecting the higher order factors, can be calculated by:

$$C = \frac{\varepsilon}{d}\int_{-a}^{a}\int_{-a}^{a}\{1+\frac{W(x,y)}{d}\}dxdy \quad (14)$$

And by replacing (8) in (14), the capacitor for a square aperture is obtained as follows:

$$C = C_0(1+\frac{12.25Pa^4}{2025dD}) \quad (15)$$

As $C_0$, the zero pressure capacitance, is given by:

$$C_0 = \frac{4\varepsilon a^2}{d} \quad (16)$$

The sensor sensitivity is defined as [5]:

$$S_A = \frac{dC}{dP} \quad (17)$$

Thus, according to (15), the sensor sensitivity with square diaphragm is obtained as:

$$S_A = \frac{49\varepsilon a^6}{2025d^2D} \quad (18)$$

This formula can't be satisfied the stepped diaphragm. In stepped diaphragm, the air gap varies between the diaphragm and lower electrode. Therefore, taking into account the relationship between the area of the square and its side, by replacing $a^2$ with $A/4$ in (15), the capacitance can be expressed as:

$$C = C_0(1+\frac{12.25P(A/4)^2}{2025dD}) \quad (19)$$

Where $A$ is the diaphragm area. It is possible to parallel the two capacitors with different air gap (see Fig. 4b), so the total capacitance for stepped diaphragm calculated as follows:

$$C = \frac{C_{01}(1+12.25P(A_1/4)^2)}{2025d_1D} + \frac{C_{02}(1+12.25P(A_2/4)^2)}{2025d_2D} \quad (20)$$

Where $A_1$ and $A_2$ are the diaphragm areas with $d_1$ and $d_2$ air gap, respectively (see Fig. 4a). $C_{01}$ and $C_{02}$ are the related capacitances in zero pressure.

$$C_{01} = \frac{4\varepsilon(A_1/4)}{d_1} \quad (21)$$

$$C_{02} = \frac{4\varepsilon(A_1/4)}{d_2} \quad (22)$$

According to (17), the sensor sensitivity with stepped diaphragm is calculated as:

$$S_A = \frac{49\varepsilon(A_1/4)^3}{2025d_1^2D} + \frac{49\varepsilon(A_2/4)^3}{2025d_2^2D} \quad (23)$$

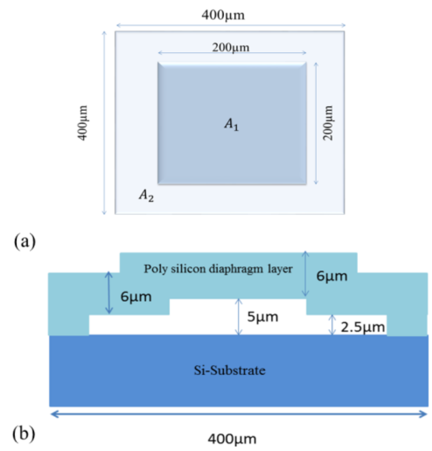



**Fig. 4**. Picture of suggested new structure of sensor a) top view b) cross section view

Sensitivity of a capacitive pressure sensor in its operating pressure range can be analytically defined as the slope of a straight line obtained by the least square linear curve fitting over its C – P characteristics plot. Based on this straight line, non-linearity, NL, in percentage could be defined as [22]:

$$NL = \frac{|\Delta C_+| + |\Delta C_-|}{2(C_{max} - C_{min})} \times 100 \quad (24)$$

Where $\Delta C_+$ and $\Delta C_-$ are the maximum and minimum deviation from the straight line characteristics respectively, $C_{max}$ and $C_{min}$ are the maximum and minimum capacitance in the operation range.

## 4. RESULT AND DISCUSSION

First, a MEMS capacitive pressure sensor with square flat diaphragm ( $400 \times 400\,\mu m^2$ ) with thickness of 5µm made of poly silicon was examined under pressure between 0 and 300 KPa. Fig. 5 shows the central displacement of diaphragm using analytical and finite element analysis (FEA) methods. As shown in Fig. 5, the central displacement of diaphragm increases when the pressure has been increased. The simulation results for two flat diaphragms with different thicknesses are presented in Fig. 6. As expected from (5) and (7), by increasing the diaphragm thickness, the central displacement of diaphragm and the mechanical sensitivity will be considerably decreased. Fig. 7 shows the capacitance of sensor versus applied pressure. From the Fig. 7, despite the sensitivity of the sensor is reduced from 0.126 $fF/KPa$ with diaphragm thickness of 5µm to 0.063 $fF/KPa$ with thickness of 6µm, the non-linearity is significantly improved from 4.49% to 2.37%.

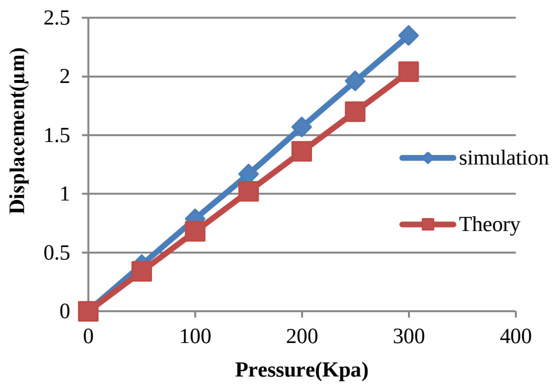



**Fig. 5**. Diaphragm displacement under various pressures for flat diaphragm with 5µm thickness

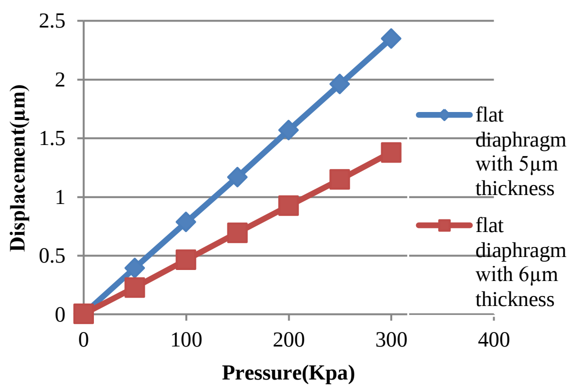



**Fig. 6**. Diaphragm displacement under various pressures for flat diaphragms with 5µm and 6µm thicknesses

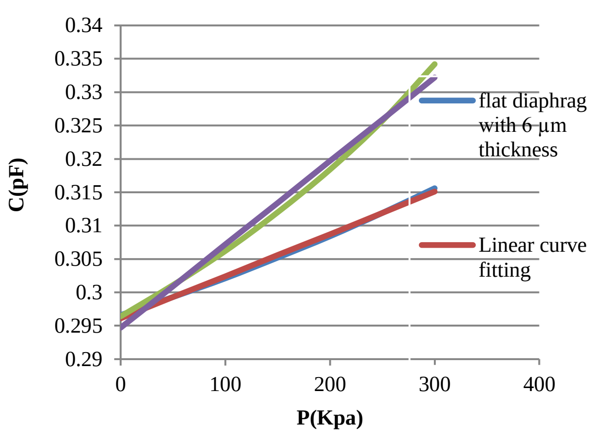



**Fig. 7**. The capacitance of sensor versus applied pressure

To achieve high sensitivity, the flat diaphragm is turned to a stepped diaphragm. The simulation results for two flat and stepped diaphragms are shown in Fig. 8. It can be seen that, the movement of stepped diaphragm under same pressure has been decreased in comparison with flat diaphragms due to the increasing of stress at the diaphragm edges and center (Fig. 9). Figure 10 shows the capacitor versus pressure for flat and stepped diaphragms with 6µm thickness. It can be seen that using non-uniform air gap increases capacitance. From Fig. 11, the simulated sensitivity is 0.107 $fF/KPa$ whereas the calculated one is 0.128 $fF/KPa$. The difference between the simulation and the theoretical results is due to the approximation of the formula. In addition, the non-linearity is obtained 1.857% with stepped diaphragm (see Fig11). Thus using new design the sensitivity and linearity are improved simultaneously.

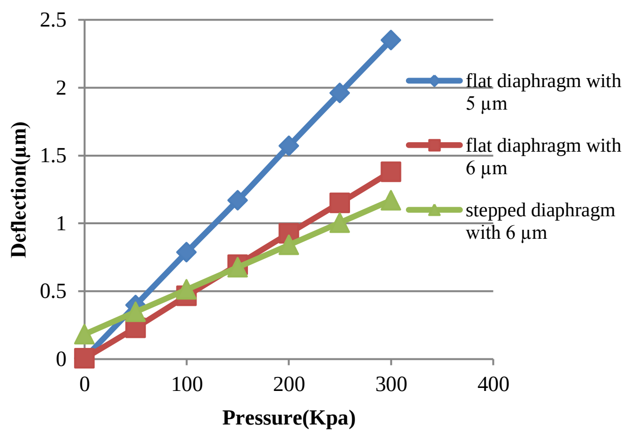
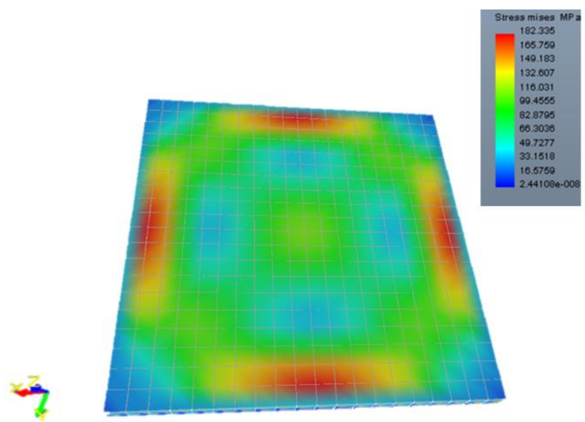
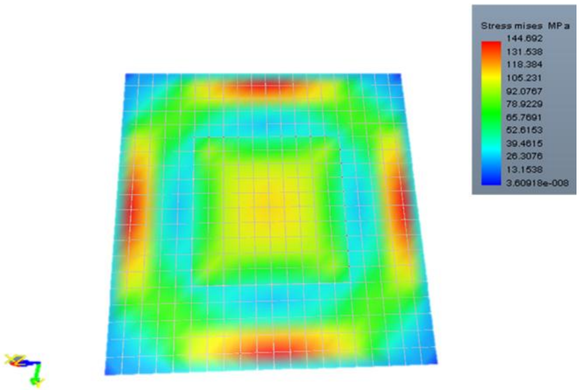



**Fig. 8**. Diaphragm displacement versus pressures for flat and stepped diaphragms



(a)




(b)

**Fig. 9**. Stress distribution on a) flat diaphragm b) stepped diaphragm with 6µm thickness under same pressure

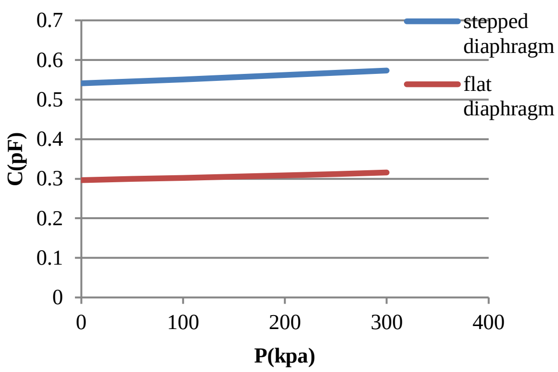



**Fig. 10**. The capacitor versus pressure for flat and stepped diaphragms with 6µm thickness

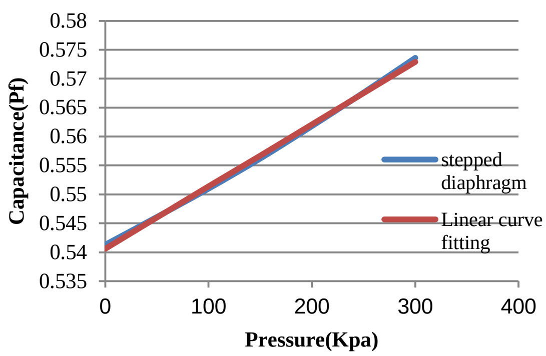



**Fig. 11**. The sensitivity and non-linearity of the stepped diaphragm with 6µm thicknesses

## 5. CONCLUSION

In this paper, a new capacitive pressure sensor for tire monitoring system is designed and simulated. In this study, by increasing the thickness of the diaphragm, and converting it to stepped one, the sensitivity and linearity of the sensor are substantially improved. The results show that the sensitivity of the sensor is increased from 0.063 Ff/KPa with flat diaphragm to 0.107 Ff/KPa with stepped diaphragm and also the non-linearity is decreased from 2.37% to 1.857%. The sensitivity of the tire pressure sensor with stepped diaphragm is at least 1.6 times more than with flat one.

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