Retraction

Retraction: 50mv/Bar Sensitivity; Piezoresistive MEMS Altimeter Design for The Agricultural Drones (IOP Conf. Ser.: Mater. Sci. Eng. 1145 012088)

Published 23 February 2022

This article (and all articles in the proceedings volume relating to the same conference) has been retracted by IOP Publishing following an extensive investigation in line with the COPE guidelines. This investigation has uncovered evidence of systematic manipulation of the publication process and considerable citation manipulation.

IOP Publishing respectfully requests that readers consider all work within this volume potentially unreliable, as the volume has not been through a credible peer review process.

IOP Publishing regrets that our usual quality checks did not identify these issues before publication, and have since put additional measures in place to try to prevent these issues from reoccurring. IOP Publishing wishes to credit anonymous whistleblowers and the Problematic Paper Screener [1] for bringing some of the above issues to our attention, prompting us to investigate further.

[1] Cabanac G, Labbé C and Magazinov A 2021 arXiv:2107.06751v1

Retraction published: 23 February 2022
50mv/Bar Sensitivity; Piezoresistive MEMS Altimeter Design for The Agricultural Drones

Prathyusha Sunkari¹, Avinash Sharma², M Sushanth Babu³, Jyothsna Undrakonda¹, Sreenivasa Rao Ijjada⁴,
¹PhD Scholar, Department of ECE, GITAM deemed to be University, India
²Professor, CSE Department, M.M. Deemed to be University, Mullanaka, Haryana, India
³Professor, Department of ECE, Matrusri Engineering college, S?idabad, Hyderabad, Telangana, India
⁴Asst. Professor, Department of ECE, GITAM University, India
¹prathyusha.415@gmail.com, ²asharma@mmumullanaka.org
³sushanth19.m@gmail.com, ⁴jyothsna.1511@gmail.com, ⁵sijjada@gitam.edu

Abstract. The technology innovations and adoptions outbreaks in the field of agriculture for the ease of forming and productivity improvement. Particularly, drones usage in this sector is very necessary for several activities like spraying pesticides and monitoring the crop growth all over the farm without human intervention. Earlier, the rules of Federal Aviation Administration (FAA) Sheldon the use of drones for the farm fields. Now, the FAA liberalized their guidelines in order to encourage the technology to be part of the farming. Usually, drones should be operated at a specific altitude and fixed drones flying above 130m from the ground level having security and privacy concerns. Hence, in order measure altitude of the drone, Micro electro mechanical systems (MEMS) based Altimetry pressure sensors usually preferred in the drone, but in order to decrease the payload of the drone, a miniaturized MEMS based altimetry pressure sensor with high figure of merit design are highly need. In this paper, an attempt is made to design an Edge Centric Polycrystalline Piezoresistive MEMS (ECPP-MEMS) pressure sensor of 1000µm x 1000µm square structure, 1µm membrane thickness and X shaped strain gauge to achieve the sensitivity of 50mV/bar. This model should support to measure the pressure at low altitude (< 50m above sea level) in the pressure range of 0.1- 1 bar at ambient temperature.

Keywords: Piezoresistive, altimetry MEMS pressure sensor, FEM modelling, COMSOL

1. Introduction

MEMS Pressure Sensor: The initial MEMS based gadgets to be produced was micro pressure sensors. Till now over 18% of MEMS-based gadgets available these days were pressure sensors. MEMS pressure sensors run mostly on mechanical deformation of the thin diaphragm because of the pressure applied. Using capacitive [11], piezoresistive, resonant, optical sensing systems, the mechanical stress produced due to an applied strain is transformed into an electrical signal. Piezoresistive model is also the most commonly used amongst these numerous transduction mechanisms available for the sensor due to its several advantages like strong high efficiency, linear relationship, small scale, quick compensation circuitry, fast circuitry integration & another well-developed piezo resistance was its characteristic of shift in resistivity of some materials on stress/strain application. In order to calculate the applied pressure, Piezoresistive pressure sensors use this principle. Piezoresistive sensors often have significantly greater sensitivity than metal strain gauges that operate due to geometrical
deformation on basis of resistance change [1]. The design of the Meander piezoresistive pressure sensor configuration forms an important component of the demand for pressure sensors. In positioning a total width of piezo resistors within the long & narrow high stress areas, such types of sensors were useful mostly because of its high sensitivity & strong linearity. Due to its excellent repeatability & sensitivity, piezoresistive pressure sensors use poly silicon, silicon, as piezoresistive materials. For industrial usage, pressure sensors that use other materials such as diamond & Sic for piezo resistors are not very common because its production technology for these materials is not developed [10]. Through ion implantation, silicon-based piezo resistors will also be conveniently manufactured as well as the sheet resistance of resistors can be controlled by ion implantation. Throughout this work, we will analyse the system design & simulation of the meander form piezoresistive pressure sensor based on silicone piezo resistance. Basic Principle of pressure sensor Figure 1 shown in below:

**Figure 1. Basic Principle of pressure sensor**

In our real-life systems, pressure is a major feature. Pressure is expressed as force per unit area; mathematical expression of pressure, P is given as:

\[ P = \frac{F}{A} \]

Where, F-force applied and A-area where force is applied

When the pressure is applied to the sensor, the pressure sensitive part that generates an electrical signal at the output is deformed; this is the fundamental concept of pressure sensor.

MEMS sensor is made in micro scale with integrations of both electrical and mechanical mechanisms. The great advantage of MEMS devices is that wide adaptability with the semiconductor IC fabrication process, which reduces the cost of each sensor and one more novelty with this emerging technology is both sensing and actuation. Figure 2 shows the basic working principle of a MEMS device.
MEMS Altimeter: Altimetry MEMS-PSs are used to measure Altitude of the MAV [2] with change in atmospheric pressure. The atmospheric pressure changes with the altitude, the change in pressure is calculated in corresponding the change in resistance applied of the piezo resistors. In this work, different structures and different gauge factors of Piezo resistors are designed and FEM simulations are observed in the COMSOL Multphysics software and discussed sensitivity analysis. FAA has laid security and privacy policy for agricultural drones on usage of agricultural drones that they are not supposed to fly over 130m above sea level for application of pesticides spraying or any agricultural operation. For low altitude applications [3], the relation between pressure and altitude is given by Equation (1)

$$H = \frac{T_o}{L} \left( 1 - \left( \frac{P_s}{P_o} \right)^\frac{L R}{g} \right)$$  (1)

Where,
- $P_s$ - static pressure at H altitude in Pa
- $P_o$ - standard pressure at sea level (101325 Pa)
- $T_o$ - absolute temp at mean sea level(300K)
- $L$ - lapse rate at mean sea temperature with altitude (-0.0065 K/m)
- $H$ - altitude in meters(m)
- $g$ - gravity (9.80665 m/s$^2$)
- $R$ - ideal gas constant (8.3144 J/Mole K)

The Altimeter in an agricultural drone for the altitude range 10-150m above the sea level with respective to the equation 1, the graph is presented in the Figure 3.

Piezoresistive pressure sensors (PPS): PPSs works on the principle of change in resistance of the piezoresitive elements on the membrane for the applied pressure [12]. This sensing technology is most widely used compared to other sensing methodologies like capacitive (change in capacitance) and piezoelectric (generation of electric charges) counterpart due its high sensitivity, high performance, good reliability, smaller size and simple signal conditioning circuit, but it requires additional temperature compensation circuit in these type of applications where ambient temperature varies w.r.t time because these type of sensors performance is highly variable with temperature. But otherwise, some applications where temperature is constant over time piezoresistive pressure sensors are good choice.
**Altimetry Piezoresistive pressure sensors:** Generally, Piezoresistive pressure sensors are of three types such as Absolute Pressure sensor, Gauge Pressure sensor and Differential Pressure sensor. The current application to estimate height (H) of the drone above sea level w.r.t pressure (P) at that height comes under Absolute pressure since it is measure of relative to vacuum as shown in Figure 4. According to theory of plates Pressure and deflection in membrane [5] is given by Equation (2):

\[
P = Y \left( \frac{2a}{h} \right)^4 \left[ 4.54 \frac{w}{h} + 2.33 \left( \frac{w}{h} \right)^3 \right]
\]

Figure 4. Altimetry Piezoresistive pressure sensor

Where 2a is the total length of membrane, a is distance from centre to the peripheral, h is the thickness of membrane, \(w_0\) is the deflection of membrane, Y is the young’s modulus P is the pressure difference between high pressure chamber and low-pressure chamber.

The main design consideration for calculation of altitude w.r.t to pressure is deflection in membrane (\(w_0\)) must be linearly varying w.r.t change in pressure at different altitudes for that purpose \(w_0\) ratio from Equation (2) should be very much less than 1 then \(w_0\) varies proportional to applied pressure (P) at height (H) altitude above sea level

2. Existing Work

In the existing work to measure altitude of the Unmanned Aerial Vehicle like drones or Micro Aerial Vehicle (MAV) above sea level diaphragm-based MEMS pressure sensors [4] are being used. In the work [7], the Square diaphragm pressure sensor for pressure range of 0.6 KPa to 25 KPa gives sensitivity of 5.23mV/bar In the work [6] diaphragm-based MEMS pressure sensor is designed with sensitivity of 1.7mV/bar for circular, 1.6um for rectangular and 2.1 for square diaphragm structures in pressure range of 0 to 10Pa. In the work [8] the MEMS pressure sensors are designed with perforated Si-Diaphragm structure is implemented for environmental application in pressure range of 0.1 to 1 bar with sensitivity of 15.92 mV/bar. In this work [2] MEMS -based barometric pressure sensor for drones for altitude measurement is designed with sensitivity of 34mV/bar in pressure range of 0.1 to 1.1 bar. In this work [1] A Peninsular structured diaphragm to obtain sensitivity of 37mV/bar at low pressure i.e 0 to 0.05 bar.

**Analytical modelling of Piezoresistive pressure sensor:** For any piezoresistive pressure sensor the arrangement and placement of resistors are important since the stress on the membrane due to applied pressure is not constant, resistors must be placed membrane where they influence maximum stress. Resistors influence stress across both axis and along the length of the resistive element on the membrane. Resistors on the membrane are modelled in wheat stone bridge circuit [13] as shown in Figure 5.
Figure 5. Modelling of piezoresistive elements on membrane as wheat stone bridge circuit

According to principle of wheat stone bridge if \( \frac{R_1}{R_4} = \frac{R_3}{R_2} \) then bridge is balanced that means voltage at 2 and 3 will be zero, but due to applied pressure there will be change in resistance of the piezoresistive element. so this change in resistance (\( \Delta R \)) for original resistance (\( R \)) for applied input voltage and produced output voltage for \( R_1 = R_2 = R_3 = R_4 = R \) is given by Equation (3)

\[
V_{out} = V_{in} \frac{\Delta R}{R}
\]

Where, \( V_{out} \) is output voltage to be measured, \( V_{in} \) is applied voltage to resistive network on the membrane, \( R \) is the original resistance of piezoresistive element \[9\]. \( \Delta R \) is the change in resistance of the piezoresistive element on the membrane due applied pressure for deflection in membrane.

According to laws of Elasticity Stress(\( \sigma \)) varies linearly with Strain(\( \varepsilon \)). Relation between Stress and Strain \[11\] are given by Equation (4)

Youngs Modulus of the Material,\( \frac{\sigma}{\varepsilon} = \frac{Y}{E} \) (4)

For a square membrane shown Figure 6. of length(l), width(w) and thickness (h). Piezo resistors are placed on the membrane where they influence maximum longitudinal stress (\( \sigma_L \)). The longitudinal stress at any point \( x = \pm a \) is given by Equation (5)

\[
\sigma_L = \frac{P a^2 h}{2}(1 - \delta)
\]

Figure 6. Square membrane at longitudinal stress (\( \sigma_L \)) at x=a

This longitudinal stress (\( \sigma_L \)) is not always same, it changes according to \( x = a \) from square membrane to rectangular membrane.

Piezoresistive effect: For any piezoresistive material whose crystal structure will be either p type or n type semiconductor, due to applied pressure(P) there will be change in energy band structure for which mobility of charges varies which results in resistance. In this concern term Gauge factor(G) as in Equation (6) is defined as ratio of change in resistance w.r.t strain influenced by the resistors on the membrane.

\[
G = \frac{\Delta R}{R} \frac{1}{\varepsilon}
\]

The gauge factor of different types of strain gauge is given in Table 1. In this paper piezoresistive pressure sensor is modelled using polycrystalline silicon strain gauge which gives high sensitivity and high linear performance over wide range of pressure. The gauge factor(G) in terms of geometry and material properties is given in Equation (7)

\[
\frac{\Delta R}{R} = G \frac{a^2}{h^2}(1 - \delta)
\]

Table 1. Gauge Factor of Piezo resistors depending on various materials
The sensitivity is defined as the change in output voltage ($V_0$) for change in pressure ($P$) at different altitude above sea level below 150m to the applied voltage ($V_{in}$). The sensitivity ($S$) is given by Equation (8)

$$S = \frac{AV_0}{\Delta P} \frac{1}{V_{in}}$$  

Sensitivity of sensor also depends on its piezoresistive coefficient ($\Pi$) given as in Equation (9)

$$S = \Pi_L \frac{a^2}{h^2} (1 - \delta)$$  

Where, $\Pi_L$ is the longitudinal piezoresistive coefficient, $a$ and $h$ are the geometrical parameters of membrane, $\delta$ is the poisons ratio, the material property, piezoresistive coefficient ($\Pi$) is given as ratio of gauge factor ($G$) to the young’s modulus ($Y$) i.e given in Equation (9). 

$$\Pi = \frac{G}{Y}$$  

Linearity is defined as linear variation output voltage change ($V_0$) for applied stress due to maximum pressure for maximum stress on membrane without damaging the membrane, this maximum pressure is called burst pressure ($P_{burst}$) given in Equation (10)

$$P_{burst} = \frac{\sigma_{max}}{h^2}$$  

3. Results and discussion

From the above analytical analysis of piezoresistive pressure sensor, polycrystalline piezoresistive pressure sensor is modelled and simulated using COMSOL Multiphysics FEM simulation software. A square membrane shown in Figure (7a) of dimensions 1000µm x1000µm and 1µm thickness. A p type lightly doped polycrystalline silicon piezo resistors are placed in the cross (X) shaped shown in Figure (7b) with the metal contacts at the edge centric on the n type lightly doped polycrystalline silicon membrane to obtain the sensitivity of 50mV/bar in according with the Equation (8) for the applied input voltage of 3V. The stress distribution on the surface of membrane for applied pressure of 1 bar along the edges towards the centre is shown in Figure (9).

![Figure 7a](image)

**Figure 7a.** A square membrane of 1000X1000 um dimension with 1um thickness
Figure 7b. Cross shaped edge centric polycrystalline silicon piezo resistor.

The simulation results are shown in Figure 8 at 100KPa or 1 bar of pressure at altitude of 130m above sea level, above which agricultural drones are not allowed to fly for any agriculture operation as per FAA.

Figure 8. Applied input voltage of 3V to the strain gauge modelled in COMSOL. The Figure 9 shows the stress displacement on the surface of the membrane for the applied pressure model in the COMSOL.

Figure 9. shows stress displacement on the surface of the membrane for applied pressure

4. Comparative analysis of proposed design with existing design

In the existing designs Diaphragm based Square, Circular pressure sensors are mostly used for reliability at the cost of sensitivity, but polycrystalline based pressure sensors provide both reliability and enhanced sensitivity. Proposed model in this work given increased sensitivity compared to
sensitivity of structures for pressure sensors in literature. Table 2 gives Comparative analysis of proposed design with existing design

| Model          | Diaphragm Type-material | dimensions | Pressure (bar) | sensitivity (mV/bar) |
|----------------|-------------------------|------------|----------------|----------------------|
| [6] 2012       | Perforated Si-Diaphragm | 1100 µm x1100 µm Thickness, t=7µm | 0-2           | 15                   |
| [1] 2014       | Square-Al               | 1200 µm x1200um Thickness, t =10um | 0-0.05        | 37                   |
| [7] 2015       | Square-Si               | 2900 µm x2900 µm Thickness, t =20 µm | 0-0.4         | 89                   |
| [2] 2019       | Square-Si membrane      | 1600 µm x1600µm Thickness, t =25 µm | 0-1.1         | 24                   |
| Proposed model | X-shaped Edge Centric Square - poly Si | 1000 µm x1000 µm Thickness, t =1 µm | 0-1-1.0       | 50                   |

5. Conclusion and Future Scope:
Performed analytical modelling of Piezoresistive MEMS pressure sensor for applied pressure range of 0.1-1 bar and it is shown in simulation result that Proposed design gives sensitivity of 50mV/bar using COMSOL Finite Element Modelling (FEM) software. In the present work only N type Polycrystalline Silicon membrane semiconducting material and P type Polycrystalline Silicon strain gauge is used but these designs can be further analysed for the different material properties such as Graphene and polymers to improve sensitivity with respect to Atmospheric pressure variations at different altitudes for change in temperature.

References
[1] Xian Huang DachengZhang, A High Sensitivity and High Linearity Pressure Sensor Based on a Peninsula-Structured Diaphragm for Low-Pressure Ranges, Sensors and Actuators: A Physical (2014)
[2] S. Santosh Kumar, Ankit Tanwar, Development of a MEMS-based barometric pressure sensor for micro air vehicle (MAV) altitude measurement, Microsystem Technologies-Springer Nature, 26, pp 901-912. 2020.http://doi.org/10.1007/s00542-019-04594-x
[3] Chin E. Lin, Wei-Cheng Huang1, and Chin-Chung Nien, MEMS-Based Air Data Unit with Real Time Correction for UAV Terrain Avoidance, Journal of Aeronautics, Astronautics and Aviation, 43(8), pp 103-110, 2011.
[4] A. Nallathambar, T. Shamudananthamb and D. Sindhanaiselvic, Design and Analysis of MEMS based Piezoresistive Pressure sensor for Sensitivity Enhancement, Materials
[5] S. Santosh Kumar and B. D. Pant, Design principles and considerations for the ‘ideal’ silicon piezoresistive pressure sensor: a focused review, Microsystem Technologies- Springer, 20, pp 213–1247, 2014.
[6] M. Suganya and H. Anandakumar, Handover based spectrum allocation in cognitive radio networks, 2013 International Conference on Green Computing, Communication and Conservation of Energy (ICGCC), Dec. 2013.doi:10.1109/icgce.2013.6823431. doi:10.4018/978-1-5225-5246-8.ch012
[7] Haldora and A. Ramu, An Intelligent-Based Wavelet Classifier for Accurate Prediction of Breast Cancer, Intelligent Multidimensional Data and Image Processing, pp. 306–319.
[8] Nallathambi Arjunan, “Design and analysis of perforated si-diaphragm based mems 5-pressure sensor for environmental applications”, ICTACT Journal on Microelectronics, Vol.2(1), pp.209-215, 2016.

[9] Sreenivasa Rao Ijjada and Arun Kumar Mandupu, “Design, Sensitivity Enhanced Analysis of MEMS CAPS Structures for BP and Glaucoma Measurement”, International Journal of Advanced Science and Technology, Vol-29(7), pp.8057-8066, 2020.

[10] K. P. Chong, L. Sung, D. L. Ho, M. R. Vanlandingham, “Solid Micromechanics: research and challenges”, Journal of Micromechanics and Microengineering, 2002.

[11] Sreenivasa Rao Ijjada and Arun Kumar Mandupu, “Implementation of MEMS Capacitive Pressure Sensor Design using COMSOL Software”, International Journal of Recent Technology and Engineering (IJRTE), Vol-8, (2S8), pp.967-972, 2019.

[12] Ali Abolfathi, Michael J. Brennan, “Large deflection of a simply supported beams”, thesis report, ISVR Technical Memorandum No. 988, 2010.

[13] Sreenivasa Rao Ijjada and Arun Kumar Mandupu, “Modeling and Analysis of MEMS based Capacitive sensor for Bio-Medical Applications”, Journal of Advanced research in Dynamical and control systems, Vol-12(2) pp-2373-2380, 2020.