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Dynamic modelling and analysis of MEMS-based low-pressure range capacitive sensors for biomedical applications

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Abstract

Sensitivity and linearity are promising parameters for MEMS (Microelectromechanical system) based Capacitive pressure sensors (CPS). This study discusses the basic principle, classification of the sensing mechanism and recent trends for improving the sensitivity. The review includes mathematical analysis and dynamic modelling on various parameters like deflection, and capacitance. In addition, this comprehensive study also discusses capacitive pressure sensors of different structures/shapes with their advantages and limitations. MEMS-based Capacitive pressure sensors have attracted research interest in recent years for various potential applications in the field of biological, industrial, microphones, touch screens etc. This article deals with different substrates and membrane materials for the sensor along with fabrication methodology. Existing technologies for MEMS-based Capacitive pressure sensor faces common challenges which are discussed here. Advancements in MEMS sensing technology and attractive feature of state of the art in MEMS-based low-range capacitive pressure sensors make use of it in medical applications like BP, IOP and ICP are discussed in detail. Finally, the main finding of this study shows the square shape CPS gives maximum deflection up to the range of 10 kPa.

Subject Classification: *65 Numerical analysis, 62 Statistics, 51 Geometry.*

Keywords: *Sensitivity, Capacitive pressure sensors (CPS), Blood pressure (BP), Linearity, Precision.*

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1. Introduction

The MEMS based CPS has been seeking more attention in medical science due to the potential of miniaturizations with a common application for example measurement of BP, ICP, and IOP. Human life expectancy is increasing day by day due to modernization and digitization, as we now have greater means to tackle diseases and detect them early on.

The need an hour of is highly sensitive, low cost, small in size highly efficient with small signals & large signals, less resistance tolerance, and lightweight MEMS CPS as compared to other sensors. The spacing between the two working electrodes was varied by applying pressure to the upper electrode of the parallel plate capacitor, resulting in a change in capacitance. varied by changing the upper electrode under pressure to the parallel plate capacitor, resulting in a change in capacitance.

Many researchers use different material as diaphragm membranes for commercialized applications like automotive industrial applications, aerospace and consumer application, etc. Since 2016, the research interest of researcher low-pressure range in CPS is shown in the Figure 1.

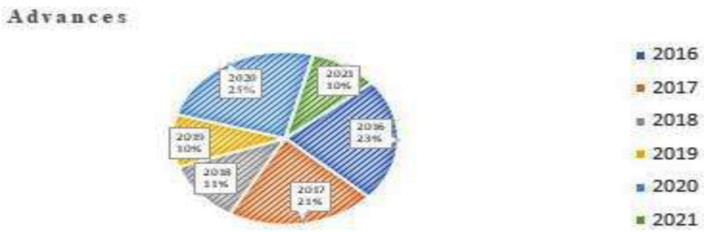

Figure 1

Recent Advancement

In the organization, the discussion starts with the sensing principle of CPS along with their ranging application. Next, recent studies have attempted to improve the sensitivity with their advantages and limitation. In addition, different type of diaphragm design is also discussed. Finally, the medical application of low-pressure range CPS is discussed in detail.

2. Classification

Micromachined MEMS-based CPS can be classified into different ranges such as low, medium, ultra-low and high based on the sensing range mechanism shown in table 1. However, the focus of this paper is

Table 1

Pressure Classification Range with their Applications

Type	Range	Application
Ultra-Low	Less than 1 Pa	Sound and human breathing
Subtle -pressure	1Pa to 1 kPa	Sensitive e-skin, touch screen etc
Low	1kPa to 10 kPa	Medical monitoring (BP, Pulse, brain etc)
Medium	10kPa to 100 kPa	For the detection of pressure and movement
High	>100kPa	special circumstances

on a confined range of medical applications with great Sensitivity and reliability.

2.1 *Proposed Technique for the Enhancement of Sensitivity*

The sensitivity of a sensor is a key factor in determining its performance. It is typically described as the rate of change of output element to the rate of change incoming input signals, which reflects the sensor's precision and efficacy in practice. A CPS sensitivity is defined as given in equation 1

$$S_c = \frac{dc}{dp} \tag{1}$$

As a result, a small capacitance will enhance sensitivity. As a result of large displacement, nonlinearity will occur. After reading available literature, it was determined that the most effective method for improving sensor sensitivity primarily involves three aspects, a) creating a microstructure (MS) of the electrode or dielectric; b) Creating a composite dielectric for polymer elastomer by adding conductive fillers and; c) incorporating micro-holes into the insulating layer. However, it is analysis that sensitivity effect by permittivity of dielectric medium, shape of the membrane and separation between the electrodes.

2.2 *Sensor Diaphragm Material & Substrate Material*

In order to achieve good sensitivity, reliabilities, and linearity, MEMS-based CPS affect by substrate, diaphragm, and dielectric materials. This section discusses the review of the research progress of Mems material with methodology. Table II shows the category of material used for MEMS CPS.

Table II

Classification of Material used for Capacitive Pressure Sensor

Classification	Material
Semiconductor	Silicon, polysilicon, SiC, Germanium, GeAs, Graphene, Silicon nanowires
Insulator	Silicon Dioxide, Silicon Hydrocarbide, Silicon Nitride (SiN), Aluminium Oxide
Metal	Aluminium, Silver, Gold, Titanium, copper, platinum
Polymer	Nylon, Polyamide, polyethylene, PVC, LCP, PMMA, Parylene, PDMS

2.3 *Effect of Structural Design for Enhancement of Sensitivity*

This technique gives low value parasitic capacitance as well as reduced hysteresis problem [2]. Another article [3] discussed how the diaphragm's design is critical to the sensor's efficiency and also investigated how various parameters affect the sensor performance.

The author discusses the different types of PS and manufacturing materials used for MEMS[6]. In this reported work a extracted [7]. Another article [8] describes the development and challenges in MEMS based PS design, model construction, simulation, and analysis. In the developed model shape, simulation results give more linearized displacement as

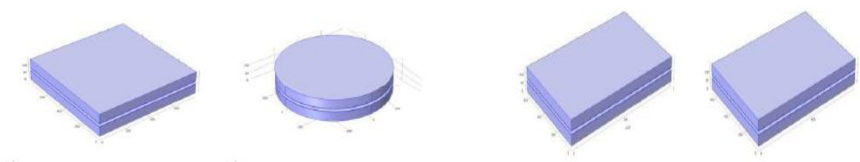

Figure 2

Different Structure Model of Capacitive Pressure Sensor [11]

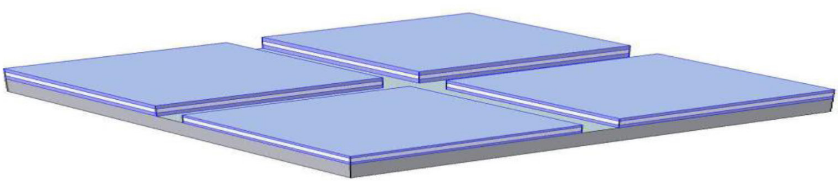

Figure 3

Diagram of Pressure Sensor Array [14]

well as capacitance at a uniform pressure. This article [11] used the three different design circular, square and rectangular, were simulated, for high pressure application as shown in the figure 2. The simulation results depict that circular shows more capacitance than other two different structure but in case of linearity output square & rectangular shaped gives better result to the circular shape in the range from Pa to 100MPa.The same researcher presented a different thickness MEMS PS array that can estimate a wide range of the pressure 0-33.25 MPa as shown in Figure 3 and Combinational switching, is used to read out output with good linearity [14]. In another article the different material for different applications were discussed [22]. It was discovered that the PS with the square shape and thinnest membrane was more sensitive than the circular and rectangular sensors [20]. Multimodal dielectric elastomer CPS that can measure the pressing pressure and location at the same time was presented in this work [24-25]. Using this multimodal sensor any single point load may be measured and the tactel easily identified. Table III shows the size & methodology of CPS with sensitivity. This hybrid sensor produces high sensitivity over a short response time and MEMS based CPS used as CMUT and pressure at a frequency of 5MHz [27].

3. Low-Pressure Range Sensors used for Medical Applications

Micro-machining technology has been developed, and thin films with a higher density are created. A low-range pressure sensor can be used for medical purposes.

3.1 *Blood Pressure*

In 2002, the substrate channels and cavity have been created using Silicon etching and SiO2 thermal growth [28]. Ion implantation was then used to create piezo-resistors by depositing an insulating layer and another layer of poly-Si. The separation between the electrodes of an ultra-small PS was designed to be 3μm [29]. In 2010, For specific application, this article [30] used three novel designs (TM, OP, and RW) with various pressure ranges. The measurement sensitivity of 193 pm/MPa has been attained in the range of 0–1 MPa. Both Splicing SMF and a solid-core photonic crystal fibre formed the micro-confocal air cavity [31]. The measurement sensitivity of 193 pm/MPa has been attained in the range of 0–1 MPa. The author [33] has demonstrated the modelling of two alternative shapes of PS with an identical area for measuring pulse rate across a large pressure

Table III

Detailed Specification of Pressure Sensor Regarding Dimensions, shape & Methodology (NA: data not mentioned in the reference)

Author	Year	Dimensions of the device	Shape/ Methodology	Results	Comments
M. Maksimovic et al. [1]	2009	2.5mm×0.5mm (top & bottom layer)	Different shapes (rectangular, trapezoid)	1.3×10^{-14}F/MPa	Reduce capacitance value
T. Pedersen et al. [2]	2009	4mm×4mm×0.5mm (chip size)	SquareHexagonal element cavity	76pF/bar	Reduced hysteresis & resolution improved
P. Eswaran et al. [10]	2012	S-750µm^2 ×3µm R-750×1000µm^2 ×3µm×5µm C-500µm, 1000µm& 3µm,5µm	Square, circular rectangular,	8.3aF/mba	Aircraft altimeter
M. S. Nateri et al. [4]	2012	50×50 µm2	T-shaped protrusion structure with slots on diaphragm membrane	3.22(F/MPa)	Stiffness, stress & air damping reduced
G.mishra et al. [5]	2012	60×60 µm^2 ×1.5µm	Square, hexagonal & circular	2.12×10^{-14}F	Square gives the best result
B. A. Ganji et al. [7]	2013	Square and circular 50 µm	Clamped Square shape diaphragm	1.71×10^{-21} M/Pa	Sensitivity& Accuracy increased
N. Anadkat et al. [9]	2015	500µm×500 µm	Square	52.8x10–6 pF/ Pa.at 25 kPa	Temperature dependent
K. B. Balavalad et al. [11]	2015	All sensor thickness 63µm	Square, circular, Rectangular	2.93×10^{-13} F/ MPa	Circular shows more sensitive
A. Dwivedi et al . [12]	2015	500×500 µm^2×2 µm	Square & circular diaphragm with edge eight and four slots	17.28 at 200Pa	Used for Bio-MEMS applications

Contd...

M.N elodar et al. [13]	2016	$0.4\times0.4mm^2\times5\mu m$	Square diaphragm	.006 Ff/kPa to 0.107 Ff/kPa	Nonlinearity decreased & used in tire application
K. B. Balavalad et al. [14]	2017	Side length and Depth 60µm Thickness1.5 to 3 µm	Combinational switching in MATLAB & COMSOL	1.09×10^{-14} F at no 2	Good linearity
C. berger et al. [15]	2017	$1\times1mm^2$ 7.5 & **30.**3 µm	Square microcavities & circular and hexagonal	$123aFPa^{-1}$ mm^2	NA
M. Sanaeepour et al. [16]	2017	$30\times30nm^2$ Cavity size and $10\times10nm^2$ membrane	Square	2300 pA/A/pa	Reduce the sensible pressure range
k.bhol et al. [17]	2017	$200\times200\mu m^2\times2\mu m$	Square& circular	NA	Used in the lubricating system
R.B.Mishra et al.[18]	2019	Diaphragm thickness 7 µm and semi-major &minor axis lengths varied from 100 to 300 µm	Elliptical& circular Diaphragm	Improved sensitivity	Nonlinearity occurs, reduces dynamics range
S.suman et al. [19]	2020	$500\times500\mu m^2\times10\mu m$	Square	62.84 × 10− 6 pF/Pa	Linear characteristics
M.Šiškins et al. [21]	2020	$1\times1mm^2$ array	Square array	47.8 a Pa−1 mm−2.	More flexible, portable
A.kumar M et al. [23]	2020	$300\times300nm^2\times2nm$	Square membrane	2.5 X 10-6 pF/ kPa,	BP monitoring
R Chuai et al. [26]	2020	95µm	circular	0.0097&0.0066 Pf/kPa	More linearity

range. Many vascular diseases, such as coronary heart disease, are currently caused by arterial blockages. As a result, medical catheters with small PS could be injected into vessels with suspected lesions for IO. Based on an in situ-printed air cavity, an optical fibre tip F-P interferometric PS was developed [34]. A microfibre PS based on an in-fibre confocal cavity has been demonstrated by [35]. In other article discussed a microsystem device that can be used to continuously check the blood pressure of patients and provide a warning message signal when the pressure is high or low [36-38].

3.2 *Intraocular Pressure*

The sensor used to detect IOP was slightly thicker by 2×2 mm^2 when compared to the blood PS. The electrical signal of PS used to determine IOP was often transmitted wirelessly [39-40]. In the IOP sensor, data has been transferred directly through an external device or stored in on-chip memory [41].

Another IOP telemetry system was designed to monitor the pressure and body temperature of small animals over time. For 1–2 months, the system could record IOP at a rate of 0.25 Hz with 0.3 mmHg precision and little drift [45-46]. Cancer biomarker discovery and quantification in human blood are critical for the early diagnosis of diseases, for the detection of cancer markers, a new Au-NP -modified capacitive sensor was created by reducing the application time and cost. This is used for early cancer diagnosis, which is the most critical stage of treatment [47-48].

3.3 *Intracranial Pressure*

Monitoring ICP (intracranial pressure) is critical in diagnosing central nervous system autoimmune disorders. Classic lumbar puncture involved a puncture needle being used to drain cerebrospinal fluid into an externally u-shaped tube. This procedure was difficult, time-consuming, and may have resulted in the patient suffering additional trauma or harm. For pressure measurement, a small PS might be put into the puncture needle, making ICP measurement more convenient and accurate. lumbar puncture is a technique for measuring ICP and extracting cerebrospinal fluid for analysis [49].

Table IV

Brief summary of Low-range Pressure Sensors used for Medical Applications. (NA: data not mentioned in the reference)

Applications	Year	Ref	Methods	Comments	Results
Blood Pressure	2002	[28]	Thermal growth	To create a cavity & channel	NA
	2010	[29]	Ion Implantation	Ultra-small pressure	2.0 V/Vmm/hg
	2012	[31]	splicing & SMF	Micro-confocal air cavity	High contrast & high resolution
	2013	[32]	optical 3D-printing setup	miniature F-P cavity	Cavity length changed due to applied pressure
	2018	[34]	situ-printed air cavity	Optical Tip F-P interferometric PS	High sensitivity
	2018	[35]	in-fibre confocal cavity	Miniature fibre PS	2.93 nm/MPa
	2019	[36]	Bulk micro-machining.	MEMS CPS	Continuous monitor of Bp
Intraocular Pressure	2010	[40]	NA	IOP Sensor	Data transmitted through an external storage chip
	2011	[42]	32-membrane capacitor array	HA series LC resonator	18.5 Hz/mmHg
	2012	[43]	Short suspension by cutting grooves	Groove diaphragm	Minimize diaphragm stiffness and residual stress
	2012	[44]	Gold nanodot array	optical PS	Used for reflectance
	2014	[48]	Cerebrospinal fluid through a puncture needle	nanoparticle-modified capacitive sensor	Used for precise and early cancer diagnosis

Contd...

Intracranial Pressure	1998	[49]	ICP measurement	lumbar puncture	Difficult, time-consuming
	2014	[50]	Laser cutting/HF wet chemical etching	piezoresistive PS	Measurement of disorder
	2015	[51]	NA	Thin film PS	2.85 V/kPa, supine adult's ICP

A lumbar puncture is also a non-invasive approach for monitoring ICP in clinical settings [51] thin film PS corresponding to supine adult's ICP (0-2kPa). Table IV is a brief summary of low-range pressure sensors used for medical applications such as BP etc.

Biocompatibility Issue

Short-range or IO (intraoperative) real-time measurements of BP, IOP, and ICP were commonly used. The impact of the biological environment on the long-term implantation of PS should be studied [52]**.** Another option for protecting the resistors has been to place piezo resistors behind the diaphragm membrane, as several sensors have done previously. Electrical resistance could not contact the biological environment because of this built-in separation [53].

4.1 *Challenges*

The challenge for MEMS capacitive pressure sensor technology is listed below:

1. To achieve a higher sensitivity over wide pressure ranges on a small amount of chip space.
2. To eliminate stiffness & nonlinearity that occurred in the response of the Silicon & polymer-based capacitive sensor while maintaining the large pressure range.
3. To enhance reliability while improving the sensitivity for a small pressure range sensor.
4. To enhance accuracy in the response time of Polymer-based pressure sensors.

5. To eliminate the brittle fatigue challenge that occurred in Silicon-based membrane sensors.
6. To remove the hysteresis error in touch mode CPS.

5. Conclusion

This paper is a critical study of the MEMS-based CPS for different approaches that affect the sensitivity of CPS. This study reveals the advantages and disadvantages of MEMS-based CPS, particularly the methods for increasing sensitivity. According to these studies, pressure sensor sensitivity has been significantly enhanced, resulting in the high potential use of PS in e-skin, medical monitoring, etc. The basic principles of a capacitive pressure sensor and the classification of the sensing mechanism are discussed in detail. The resultant structure affects the sensitivity of MEMS-CPS depicting that low-pressure range is used for medical monitoring such as BP, IOP, ICP, etc.

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