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Title

Design and Modeling of a Micro Pressure Sensor for Biomedical Applications

Defended before the jury composed of:

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Dedication

First, I thank God Almighty for granting me this work.

To my dear parents, a token of their love, affection, and support since my birth. For all their efforts and sacrifices in my education, they taught me to work hard until the end to achieve success. I cannot find enough words to thank them; words fail to express my deep gratitude, love, and respect. I ask God Almighty to grant them long lives and good health and happiness.

I also extend my sincere thanks to my supervisors, Dr. Lakhdari Abdelghani and Dr. Harhouz Ahlam, and I say to them: "May God reward you for your tireless efforts and constant care."

I also thank all my teachers, from elementary school to university, who helped me reach where I am today. I say to them: "May God bless you and your efforts."

I am also pleased to mention my family, who stood by me during these difficult circumstances, and my dear friends. May God protect you and guide your steps.

I also extend my heartfelt thanks to the members of the examination committee for accepting to evaluate this humble work. I deeply appreciate their valuable time, thoughtful efforts, and constructive feedback.

I also pray for mercy and forgiveness for our martyrs in Gaza, and a speedy recovery for their wounded. I ask God to lift the injustice and affliction from them. Amen, Lord of the Worlds.

إهداء

أولاً، أحمد الله تعالى على منحي هذا العمل.

إلى والديّ العزيزين، عربون حبهما وعطفهما ودعمهما لي منذ ولادتي. على كل ما بذلاه من جهد وتضحيات في تعليمي، علّماني العمل بجدّ حتى النهاية لتحقيق النجاح. لا أجد كلماتٍ كافيةً لشكرهما، فالكلمات تعجز عن التعبير عن امتناني العميق ومحبتي واحترامي. أسأل الله تعالى أن يمد في عمرهما ويمتعهما بالصحة والسعادة.

كما أتقدم بالشكر الجزيل لمشرفيّ، الدكتور لخضاري عبد الغني والدكتورة حرحوز أحلام، وأقول لهما: "جزاكما الله خيرًا على جهودكما الدؤوبة وسهركما من اجلنا".

كما أشكر جميع أساتذتي من المرحلة الابتدائية إلى الجامعة، الذين ساعدوني على الوصول إلى ما أنا عليه اليوم أقول لهم: "بارك الله فيكم وفي جهودكم".

كما يسرني أن أذكر عائلتي التي وقفت بجانبي في جميع الظروف الصعبة وأصدقائي الأعزاء حفظكم الله وسدد خطاكم.

كما أدعو بالرحمة والمغفرة لشهدائنا في غزة والشفاء العاجل لجرحاهم أسأل الله أن يرفع عنهم الظلم والبلاء. آمين يا رب العالمين

Summary

Summary

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Abstract

Abstract

This memory focuses on the modeling and design of a pressure sensor for biomedical applications. The sensor is a capacitive MEMS (microelectromechanical systems) device used to measure blood pressure. Its sensing element is a thin circular silicon membrane [100], tightly clamped at the edges and subjected to a uniform static pressure. The analysis was performed assuming small deformations.

In the first part of the work, the mechanical behavior of the membrane was studied. Based on accurate mathematical equations, we modeled the membrane deformation, capacitive response, and sensor sensitivity using MATLAB. The results demonstrate a linear capacitive response over a pressure range of 0 to 40 kPa (0 to 300 mmHg), with high sensitivity. These results were validated through numerical simulations using COMSOL Multiphysics.

In the second part of the memory, the capacitive pressure sensor was integrated into a conditioning circuit simulated using PSPICE. The circuit's output voltage varies linearly with the applied pressure.

Keywords: MEMS, capacitive pressure sensor, membrane, silicon, sensitivity, COMSOL Multiphysics, PSPICE

Résumé

Cette mémoire porte sur la modélisation et la conception d'un capteur de pression pour applications biomédicales. Ce capteur est un dispositif MEMS (systèmes microélectromécaniques) capacitif utilisé pour mesurer la pression artérielle. Son élément sensible est une fine membrane circulaire en silicium [100], étroitement serrée sur les bords et soumise à une pression statique uniforme. L'analyse a été réalisée en supposant de faibles déformations.

Dans la première partie du travail, le comportement mécanique de la membrane a été étudié. À l'aide d'équations mathématiques précises, nous avons modélisé la déformation de la membrane, la réponse capacitive et la sensibilité du capteur à l'aide de MATLAB. Les résultats démontrent une réponse capacitive linéaire sur une plage de pression de 0 à 40 kPa (0 à 300 mmHg), avec une sensibilité élevée. Ces résultats ont été validés par des simulations numériques avec COMSOL Multiphysics.

Dans la deuxième partie de la mémoire, le capteur de pression capacitif a été intégré à un circuit de conditionnement simulé avec PSPICE. La tension de sortie du circuit varie linéairement avec la pression appliquée.

Mots-clés : MEMS, capteur de pression capacitif, membrane, silicium, sensibilité, COMSOL Multiphysics, PSPICE

ملخص

تركز هذه المذكرة على نمذجة وتصميم مستشعر ضغط للتطبيقات الطبية الحيوية. هذا المستشعر هو جهاز MEMS سعوي (أنظمة كهروميكانيكية دقيقة) يُستخدم لقياس ضغط الدم. عنصره الحساس عبارة عن غشاء سيليكون دائري رقيق [100]، مُحكم الغلق عند الحواف ومُعرَّض لضغط ثابت منتظم. أُجري التحليل بافتراض تشوهات منخفضة.

في الجزء الأول من العمل، دُرِس السلوك الميكانيكي للغشاء. باستخدام معادلات رياضية دقيقة، قمنا بنمذجة تشوه الغشاء، والاستجابة السعوية، وحساسية المستشعر باستخدام MATLAB. أظهرت النتائج استجابة سعوية خطية ضمن نطاق ضغط يتراوح بين 0 و40 كيلو باسكال (0 إلى 300 مم زئبق)، بحساسية عالية. تم التحقق من صحة هذه النتائج من خلال عمليات محاكاة عددية باستخدام COMSOL Multiphysics.

في الجزء الثاني من المذكرة، دُمِج مستشعر الضغط السعوي في دائرة تكييف مُحاكاة باستخدام PSPICEيتغير جهد خرج الدائرة خطيًا مع الضغط المطبق.

الكلمات المفتاحية : MEMS ، مستشعر ضغط سعوي، غشاء، سيليكون، حساسية، COMSOL Multiphysics، PSPICE

General Introduction

In recent years, the automation, control, and monitoring of most processes has led to an increasing need for sensors. In fact, the lack of suitable sensors and actuators to connect control electronics to the external environment in most applications is the main obstacle to the development of new systems.

Sensors are widely used in many fields (healthcare, automotive, electromagnetism, and others), and are used daily to convert mechanical, chemical, or thermal events into electrical signals. They also act as detection systems for physical quantities, leveraging microelectronics technology and offering technical and economic advantages [1].

Pressure is one of the most important parameters to be measured in many types of devices. Pressure can be measured using various physical effects, such as the piezoresistance of some materials, the capacitance difference between the conductive electrodes of a device, and piezoelectricity of some materials (such as quartz). This type of device, a pressure sensor, has numerous applications, including automotive, aerospace, and medicine. The choice of a pressure sensor in a system generally depends on the desired application and the ease of integration. The most common sensors are capacitive sensors. This choice also allows for many functional properties (high pressure sensitivity and low temperature sensitivity) [2].

The highly sensitive and capacitive detection method is the most rapid detection method. The pressure capacitors are available on the vehicle's display screens. These components are sensitive to the temperature and do not have a correct function without the compensation circuits coming out. It's the search for the latest news on the pressure capacitance capacitors using microelectronic technologies and specific procedures. In comparison with conventional compression caps, MEMS caps are available with more advanced features: high compression sensitivity, production in series, efficient encryption, efficient energy consumption and interface with integrated MOS circuits [3].

The pressure capacitive capacitor is used on this site and is based on a silicium/silicium production. This is the key to the effect of geological parameters on the capacitor statistic in a pressure gauge applied to the arterial pressure measurement in the biomedical domain, at 0 to 60 kPa (0-300 mmHg).

The content of this one is divided into three chapiters:

The chapter 1 displays a review of the screen on the pressure caps using the MEMS technology.

In the second chapter, we presented a model describing the mechanical behavior of a thin silicon membrane with a perfectly clamped circular shape. We derived the expressions governing the membrane's deflection. Then, we introduced a theoretical model of a capacitive pressure sensor with a circular membrane, both at rest and under static loading conditions, as a function of the device's geometric parameters. Finally, based on the expression of the capacitive response C(p) as a function of the applied pressure, we established a model for the sensor's pressure sensitivity.

In the third chapter, we presented the structural design of the capacitive pressure sensor. We analyzed the sensor's pressure response and its sensitivity as a function of the applied pressure. The influence of key structural parameters was investigated, including the membrane area (A), membrane thickness (h), and the inter-electrode gap (d). In the fourth chapter, we implemented a suitable conditioning circuit for the capacitive pressure sensor using PSPICE software. This simulation enabled us to evaluate the overall performance of the sensor.

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Chapter I

Pressure Sensors in MEMS Technology

I.1. Introduction

MEMS (Micro Electro Mechanical Systems) sensors are electronic devices in micron or millimeter dimensions that use the microelectronics technology platform.

Among the most common sensors in industry, pressure sensors have experienced increasing growth since the 1980s. This has been particularly evident since the development of miniature silicon sensors, which leverage microelectronic techniques. Pressure sensors are widely used in automotive, process control, and biomedical applications. The basic principle of pressure sensors is to convert pressure into an electrical signal.

Before presenting the design and modeling of the MEMS pressure sensor, it is important to provide a general discussion on pressure sensors in MEMS technology. In this chapter, we briefly review the general architecture and operating principle of a silicon micromachined pressure sensor.

Pressure sensors play a pivotal role in biomedical engineering, particularly in monitoring vital signs such as blood pressure. These sensors help healthcare professionals assess a patient's cardiovascular status and prescribe appropriate exercises or treatments. With the advent of microelectromechanical systems (MEMS), pressure sensors have become smaller, more power-efficient, and more accurate, enabling wearable health monitoring solutions that support patients in real-time without disrupting their daily routines.

I.2. Description of a Pressure Sensor

A pressure sensor is a device that detects the physical force exerted by a fluid, such as blood, and converts it into an electrical signal. In medical applications, the sensor is often placed around or in contact with arteries to capture dynamic changes in blood pressure caused by blood flow. Sensors employ various physical mechanisms, including capacitive, piezoresistive, piezoelectric, and optical methods, to detect pressure changes with high sensitivity and accuracy [4]– [6]

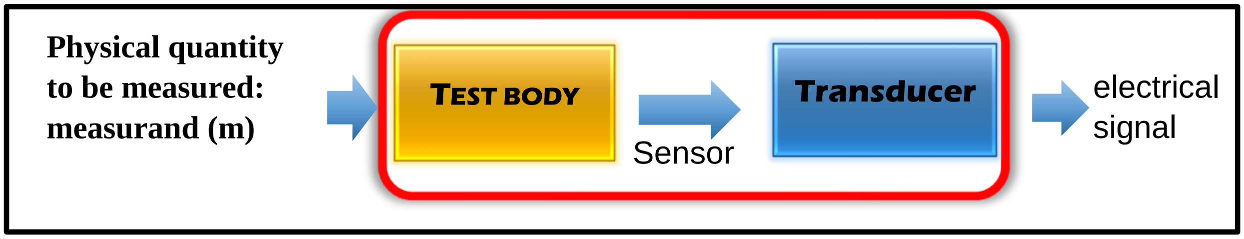


Figure I.1 Schematic diagram of a sensor

Pressure is a fundamental variable in the metrological analysis of environments, whether gaseous or liquid. This physical quantity is measured using a pressure sensor, a device that produces a recognizable electrical output — referred to as a "response" — corresponding to the measured pressure. A typical pressure sensor consists of two main components: the sensing element, commonly referred to as the sensitive cell, and the signal processing unit, known as the electronic conditioning circuit. The sensing element itself includes a sensing body and a transducer, which converts the mechanical deformation of the sensing body into a physical signal, most commonly an electrical one [6]. A pressure sensor can therefore be represented by the diagram in Figure I.2:

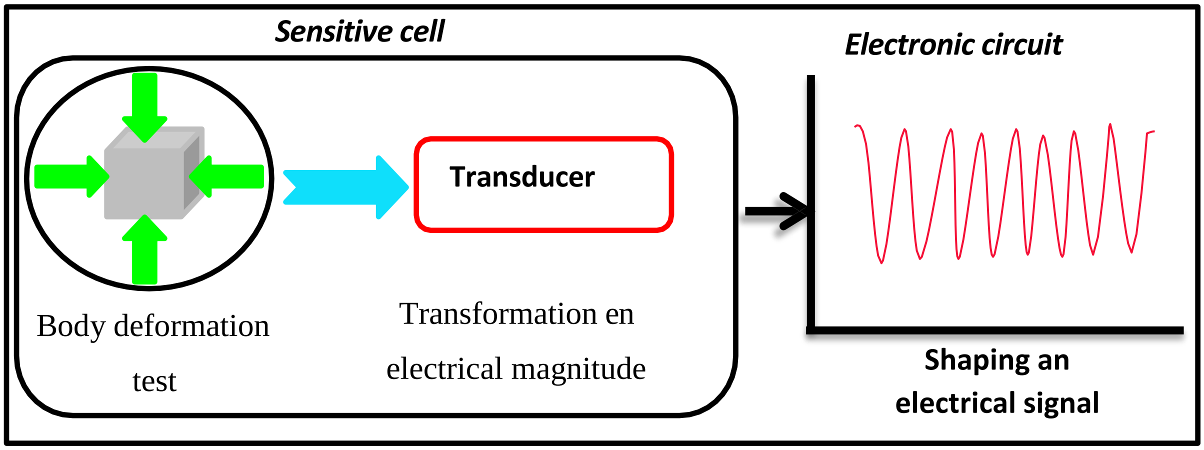


Figure I.2: Block diagram of a pressure sensor [5].

The **block diagram** of a pressure sensor consists of three essential components:

a. Sensing Element: The sensing element in a pressure sensor is a mechanical structure, typically a membrane, that converts the applied pressure into mechanical deformation. Since the 1970s, silicon membranes have become the most commonly used sensing elements due to their effectiveness and reliability [7].

b. Transducer: The transducer converts the deformation of the sensing element into an electrical signal, enabling pressure measurement based on this physical change [8]. Piezoresistive sensors detect pressure through changes in electrical resistance, but they are sensitive to temperature. In contrast, capacitive sensors are preferred due to their superior stability and sensitivit**y** [5].

c. Electronic Conditioning Circuit: The electronic conditioning circuit processes the signal from the transducer, converting it into a usable electrical output that reflects the deformation of the sensing element and, consequently, the pressure. It relies on physical laws to relate electrical signals to the measured quantity [8]

I.3. Types of Pressure sensors

I. 3.1. Capacitive Pressure Sensors

Capacitive pressure sensors operate by detecting changes in capacitance caused by the deformation of a membrane under applied pressure. The basic structure consists of two parallel plates separated by an insulating layer. When pressure is applied, the flexible membrane bends, altering the distance between the plates, which leads to a corresponding change in capacitance. This variation is then converted into an electrical signal as follows:

- The membrane, which acts as the sensing element, deforms under the influence of the applied pressure.
- The metal electrodes convert this mechanical deformation into a change in capacitance.
- The electronic processing and measurement circuit translates the change in capacitance into an electrical voltage output [9], [10]

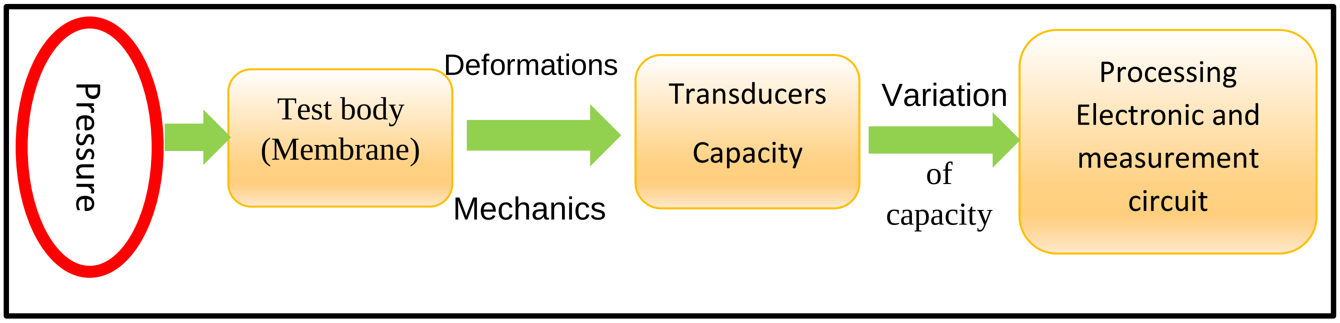


Figure I.3: Block diagram of a capacitive pressure sensor.

I.3.2.RF Pressure Sensor

This is a passive sensor. The sensor cell shown in Figure (I.4) consists of a high-resistivity silicon membrane that undergoes deflection when pressure is applied. This deflection modifies the electromagnetic environment of a coplanar resonator located beneath the membrane within a Pyrex cell. The electromagnetic field distribution is consequently modified, resulting in a variation in the resonator's frequency [9].

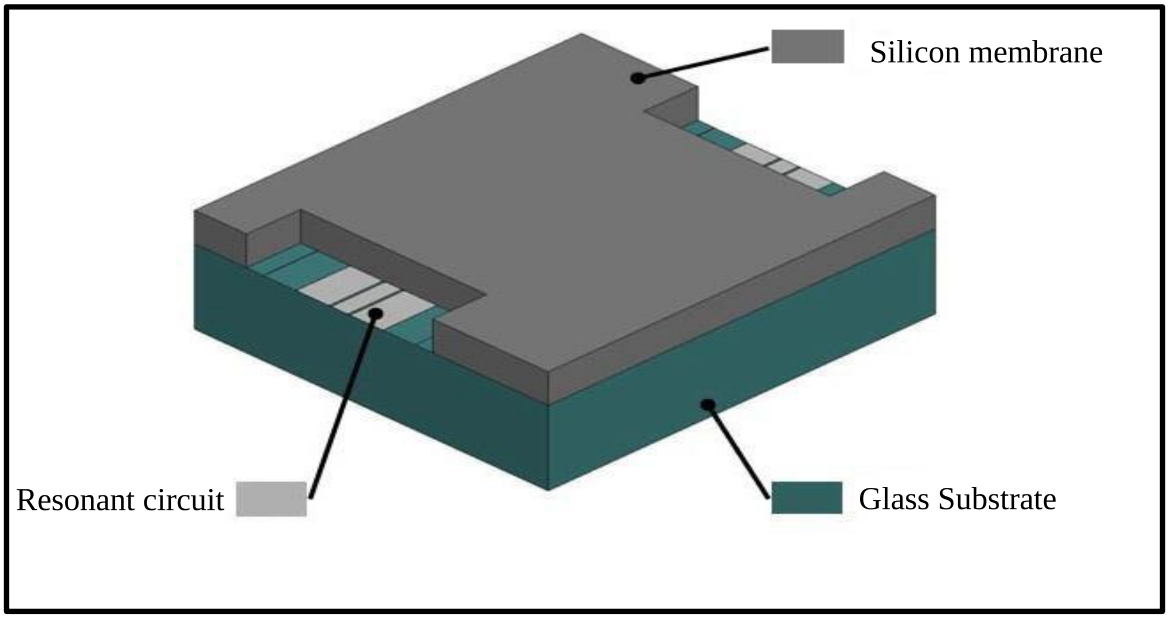


Figure I.4: The active part of an RF pressure sensor [7].

- More recent publications show that for membrane thicknesses from 50µm to 800µm, we observe a linear variation in the resonance frequency, between 0.3µm and 3µm.

This type of sensor is used in specific applications (environmental monitoring, space and aeronautical tracking instruments, health-related applications) that require miniature, passive, high-precision, and low-power measurement units. The objective is to remotely measure physical quantities [9].

RF components are less prone to drift than some traditional sensor types and can operate over longer lifespans with minimal calibration.

I.3.3. Piezoelectric Pressure Sensors

These sensors are based on piezoelectric materials that generate an electrical charge when subjected to mechanical stress. This property is used to measure the applied pressure instantly and efficiently, without the need for an external power source, making them suitable for dynamic applications such as heart rate or movement monitoring.

The most important component in Piezoelectric Pressure Sensors is the piezoelectric material, as it is responsible for generating an electric charge when exposed to pressure.

To have a high sensitivity the sensor conditioner can be made up of two longitudinal gauges and two transverse gauges arranged at the edges of the membrane and interconnected in a Wheatstone bridge by aluminum tracks, (figure (I.5)).

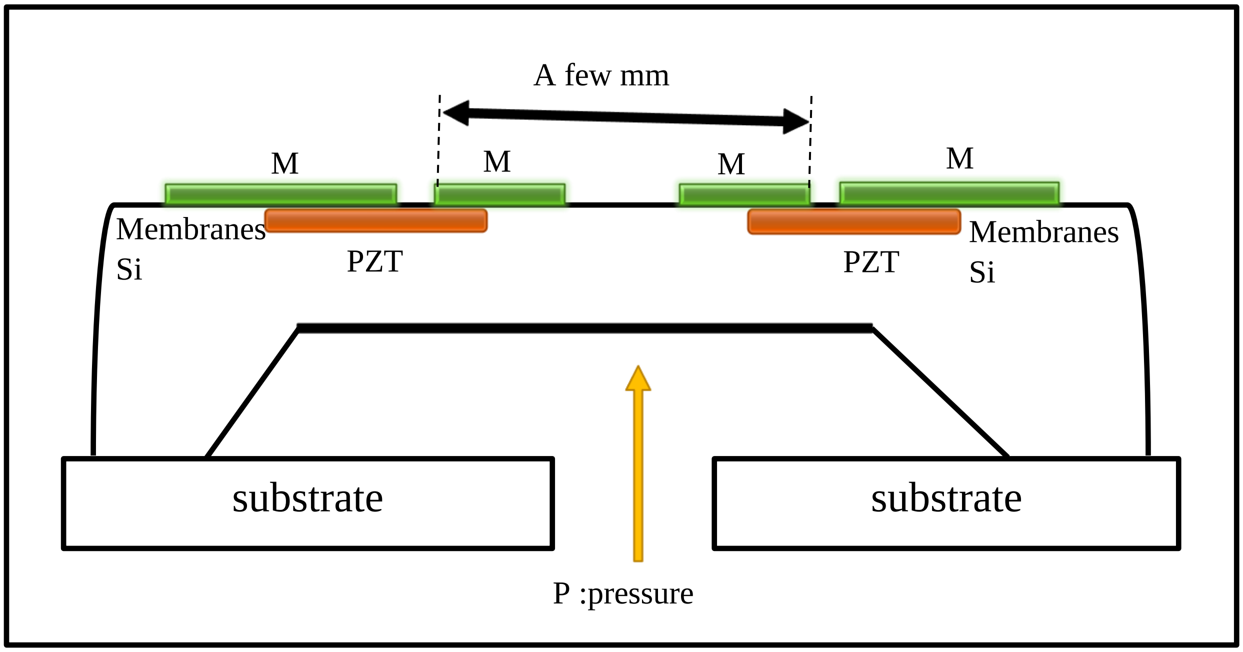


Figure I.5: Cross-sectional diagram of a piezoresistive sensor [10].

Where:

* PZT: diffused piezoresistors (strain gauges).
* M: metallizations.

Piezoelectric pressure sensors are based on the piezoelectric effect [11]. The Curie brothers discovered in 1880 that mechanical stress on piezoelectric materials generates electrical polarization. In 1881, Lippmann found the reverse: applying voltage causes mechanical deformation. (Figure I.6).

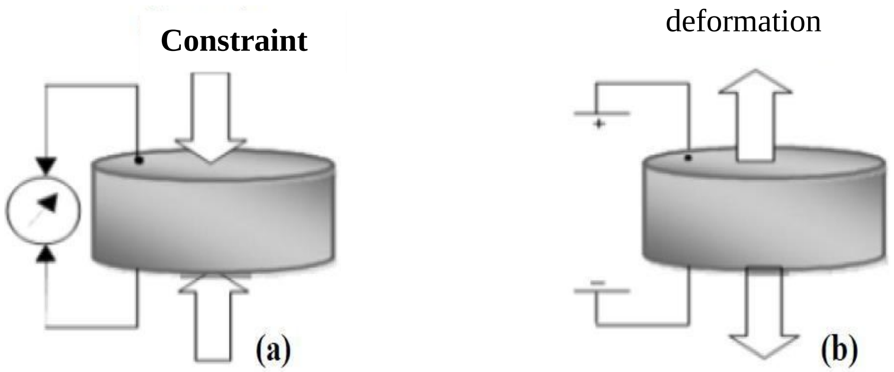


Figure I.6: The piezoelectric effect: (a) direct effect, (b) inverse effect.

Piezoelectric sensors measure pressure via voltage and are robust, small, and simple. [12]. These sensors need special wiring and are temperature-sensitive. [12, 13, 14]. Abhay B. Joshi et al [13], C. Zinck et al. simulated a piezoelectric micromechanical pressure sensor for radial artery pulse measurement using CoventorWare. The sensor design successfully met the required pressure range of 1 to 30 kPa for this application. [15] Silicon membranes with piezoelectric films were made to create sensors that convert pressure-induced deformation into voltage.

The structure and principle of a piezoelectric pressure sensor are described in Figure I.7.

• The membrane that constitutes the test body deforms under the effect of applied pressure.

• The piezoelectric material transforms this deformation into a voltage variation.

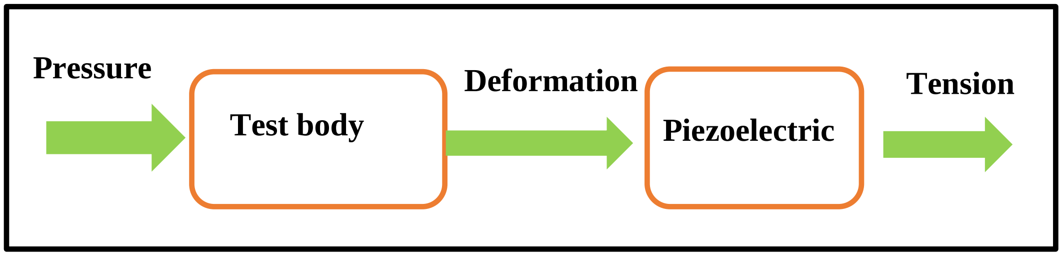


Figure I.7: Block diagram of a piezoelectric pressure sensor

I. 3.4. Piezoresistive Pressure Sensors

A piezoresistive pressure sensor monitors pressure by measuring changes in resistance. This sensor features high accuracy, low nonlinearity, and simple electronic components. This type of sensor is highly sensitive to temperature and requires a specific compensation circuit, which significantly increases the unit cost. The basic component is a silicon chip containing piezoresistive resistors.

A piezoresistive pressure sensor consists of a micromesh membrane manufactured from silicon using micromachining techniques and directional chemical agents. When the membrane is subjected to pressure, it deforms, causing a change in the resistance of piezoelectric sensors made of polysilicon placed on it. These sensors are connected using a Wheatstone bridge to convert this mechanical deformation into an electrical signal. (Figure I.8) [17].

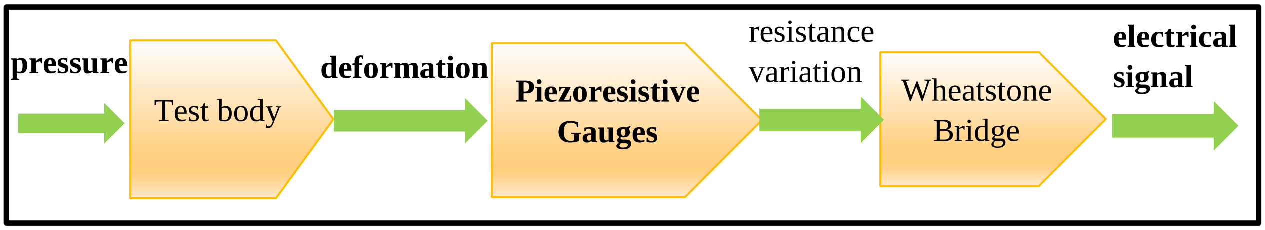


Figure I.8: Schematic diagram of a piezoresistive pressure sensor [17]

To achieve high sensitivity, the sensor conditioner can be made up of two longitudinal gauges and two transverse gauges arranged at the edge of the membrane and interconnected in a Wheatstone bridge [18] by aluminum tracks (figure I.9). The output voltage of the Wheatstone bridge supplied with constant voltage or current is proportional to the applied pressure, the polysilicon gauge factors, and the supply voltage or current.

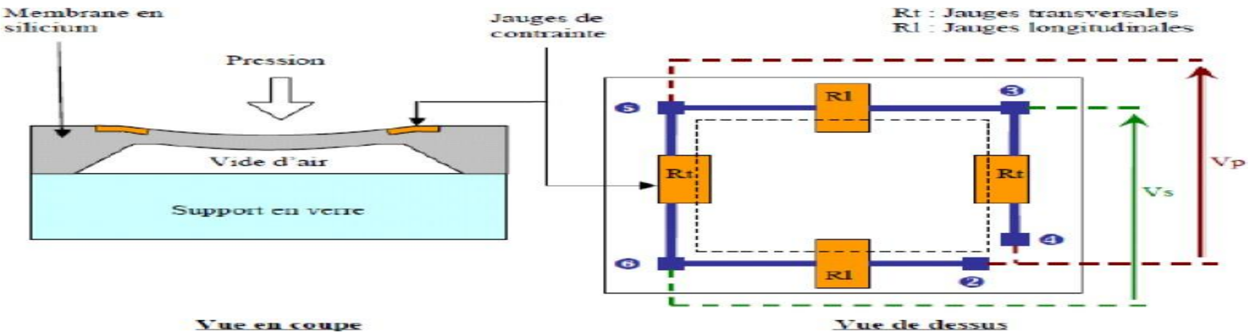


Figure I.9: Schematic Structure of a piezoresistive membrane sensor

I.3.5. Resonant Pressure Sensors

These sensors detect changes in resonance frequency caused by applied pressure. A resonating element's frequency shifts as the pressure-induced stress changes its mass or stiffness. This makes them highly accurate and useful in sensitive biomedical applications.

I.4.State-of-the-art silicon capacitive pressure sensor technology

The following are some research studies on capacitive pressure sensors:

In 1982, Wise [19] conducted research to improve the performance of silicon pressure sensors. He determined the membrane deflection as a function of temperature using a finite-difference method, without taking into account other dimensions of the sensor, and assuming constant thermal expansion coefficients for silicon and Pyrex. He derived the thermal sensitivity of a capacitive pressure sensor in a narrow temperature range between -30 and 70°C. In 1989, work by Blasquez et al. [20] demonstrated the limitations and capabilities of capacitive pressure sensors. These devices rely on the use of a thin film made of monocrystalline or polycrystalline silicon. From a metrological perspective, these sensors have high pressure sensitivity and remarkably low temperature sensitivity and can operate over fairly high temperature ranges with virtually no hysteresis. However, they exhibit a nonlinear response, which complicates their adaptation circuitry to some extent. In 1991, Kudoh [21] developed a new generation capacitive pressure sensor embedded in a CMOS integrated circuit. The electronic circuit is a frequency-capacitance converter whose oscillation frequency varies depending on the capacitance. In 1995, Elgamel [22] simulated the performance of capacitive pressure sensors under constant and uniform pressure and temperature changes. A simple and effective technique was presented, capable of representing the relationship between membrane deflection and capacitance change under constant and uniform pressure. In Eaton [23], conducted in 2000, an application for capacitive micro-pressure sensors was developed. He presented an analytical solution for a circular membrane under large disturbances. The results obtained allowed for validation of experimental results, as well as simulation models designed using the finite element method. Chapter 1: Pressure Sensors in Microelectromechanical Systems Technology Despite the increasing development of microsensors and microsystems, and the emergence of smart sensors, the study and prototyping of pressure sensors remains important. For this reason, much work is being done to improve them and enhance their performance.

In 2005, Bahri [24] focused on determining the effect of temperature on the static and dynamic behavior of silicon/glass capacitive pressure sensors over a wide temperature range (from -20°C to +150°C) and for different geometric properties.

Cheng [25] conducted more recent studies in 2007 aimed at correcting the nonlinearity of pressure sensors using a new manufacturing technique. For applications in high temperatures and harsh environments, Li [26] developed a digital capacitive strain gauge sensor. A digital capacitive strain gauge pressure sensor operates by developing capacitance between different digital conductors. Chen's work [27] in 2008 focused on the structural design and optimization of micro-pressure sensors to improve sensitivity and linearity, thereby optimizing pressure sensor parameters.

From this work, it became clear that there are some outstanding issues in the study of capacitive pressure sensors, and that their application continues to attract the interest of researchers, who aim to achieve increasingly high-performance devices.

In 2013, M. Shaheri Tabestani et al. [28] studied the analytical analysis of a square-diaphragm capacitive pressure sensor. The mechanical and electrical properties of the sensor were theoretically analyzed based on thin-plate theory under low deformation conditions, and the results were evaluated using finite element analysis. The values of the deflection at the center of the membrane and the capacitance varied proportionally with the applied pressure. Comparison of the theoretical results with the finite element analysis showed good agreement. The results indicate that the mathematical model has high accuracy in determining the sensor's behavior.

I.5. Application of Pressure Sensor

MEMS Capacitive pressure sensors are used in many different fields. For example, they help measure blood pressure in medicine, monitor pressure in factories, and check oil and air pressure in cars. figure I.10 shows some of the common places where these sensors are used

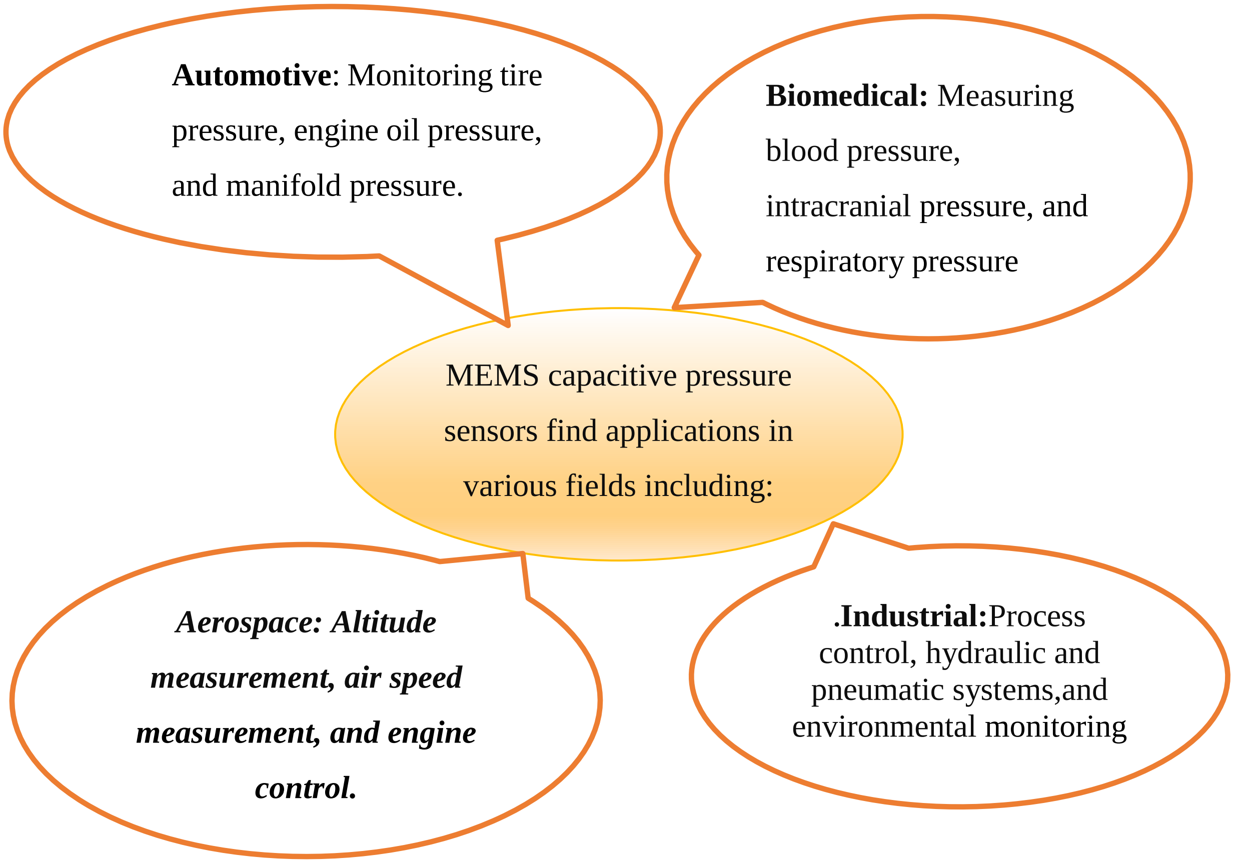
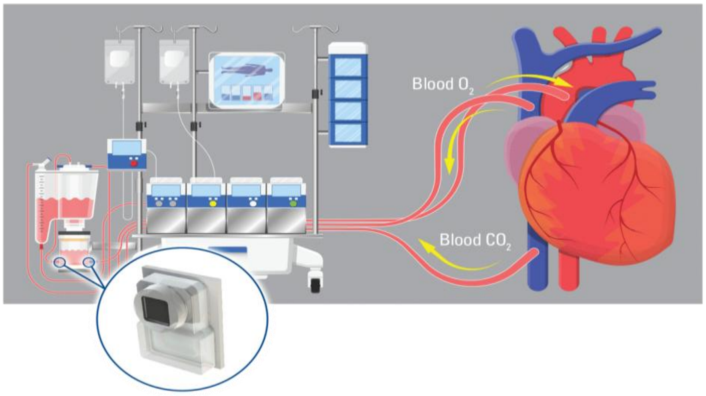


Figure I.10: Various application areas for MEMS capacitive pressure sensors.

For the medical devices the pressure sensors play a crucial role in monitoring vital signs and enhancing the performance. They are used in blood pressure monitors to measure systolic and diastolic pressure, and in ventilators to regulate airflow to the lungs. In anesthesia machines, they control gas pressure, while in ICP monitoring, they measure brain pressure accurately. Other applications include infusion pumps for drug delivery, hemodialysis machines for blood pressure regulation, and fetal monitors for tracking uterine pressure during labor.

Figure I.11: A schematic diagram showing the use of a pressure sensor in measuring blood pressure in the medical field.



I.6.Conclusion

In this chapter, we have presented the main work carried out in the field of sensors, microsensors, and microsystems. The design and performance improvement of these new components requires optimizing the characteristics of their basic elements, particularly elementary sensors based on capacitive or piezoresistive principles.

This overview shows that the study of elementary sensors continues to attract the interest of researchers in order to find solutions to the demands of the industrial market, which is becoming increasingly demanding in terms of performance. The simulation techniques used provide detailed physical and mechanical information about the structure under study. This allows for a clear understanding of the effect of influencing parameters on the meteorological characteristics of devices.

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Chapter II

Modeling of capacitive pressure sensors

II.1 Introduction

Capacitive pressure sensors represent one of the most significant applications of Micro-Electro-Mechanical Systems (MEMS) technology due to their high sensitivity, low power consumption, and long-term stability [1,2]. These sensors operate based on the principle of capacitive detection, which relies on the variation of capacitance resulting from the deformation of a flexible diaphragm under applied pressure. Structurally, the sensor consists of two parallel plates one fixed and the other acting as a flexible membrane where the distance between them changes with pressure, leading to a measurable change in capacitance.

In this context, the theoretical study of capacitive pressure sensors focuses on understanding the static mechanical behavior of the sensing cell, particularly for circular membranes with fixed edges. The deformation of the membrane as a function of applied pressure is first established, followed by the derivation of the capacitance response C(p), and finally, the sensitivity expression is obtained from this capacitive response. This approach allows for accurate modeling and optimization of sensor performance based on pressure-induced membrane deflection.

The principle of a capacitive pressure sensor is based on the variation of capacitance as a function of the pressure applied to the sensing element (membrane). The conversion of this capacitance into an electrical voltage is carried out by an electronic circuit, known as the sensor's signal conditioning circuit.

II.2 Membrane Deflection

The membrane is a component that converts the effect of the measured quantity into a non-electrical quantity to which the sensor responds. When mechanical stresses such as pressure or force are applied to the membrane, which is an elastic body, it deforms. The sensor detects the small displacements resulting from this deformation [3].

The deflection w(x, y) can be expressed as the sum of two parts: the first part is w (x, y) constant and independent of the Cartesian coordinates, and the second part $w_n(x, y)$ is independent of the pressure value:

$$W(r) = W(0,0)w_n(x, y) \qquad \text{II-1}$$

where w(0,0) represents the deflection at the center of the membrane.

In the case of a membrane with surface area S, uniform thickness h, and edges that are completely fixed, and under the assumption of small deflections, the central deflection w(0,0) can be expressed as:

$$w(x, y) = k\frac{s^2}{h^3}P \qquad \text{II-2}$$

Here:

- w(0,0) represents the maximum deflection at the center of the membrane,
- P is the externally applied pressure,
- s denotes a characteristic dimension of the membrane (such as radius or side length),
- h is the thickness of the membrane,
- k is a constant determined by the material and boundary conditions.

The deflection at the center is therefore directly proportional to the pressure. For a square or rectangular membrane, the normalized deflection W (x, y), which represents the deformation at any point on the membrane, can be approximated by a polynomial expansion of the type [4]:

$$w_n(x, y) \approx \left[1-\left(\frac{2x}{a}\right)^2\right]^2 \left[1-\left(\frac{2y}{b}\right)^2\right]^2 \left[\sum_{i,j}^{n} K_{ij}\left(\frac{2x}{a}\right)^i \left(\frac{2y}{b}\right)^j\right]^2 \qquad \text{II-3}$$

Avec :

a and b: respectively the larger and longer membrane

n, i and j: pairs of numbers

Kij: The factors depend on the membrane form and its characteristics Material mechanics.

In the case of a membrane circulator, the exact solution for the normal deflexion is given in cylindrical coordinates by:

$$w_n(r) = \left(1 - \frac{r^2}{R^2}\right)^2 \qquad \text{II-4}$$

II.3. Modeling of Capacitive Sensor

In this section, we present a theoretical model that describes the static behavior of the sensing cell in a capacitive sensor with a circular membrane.

II.3.1. Resting State

Capacitive pressure sensors consist of a machine-made silicon diaphragm, which forms the moving actuator, and an insulating substrate, which represents the fixed electrode.

These two components are bonded together by anodic welding, creating a tight cavity between the two. A schematic diagram of the capacitive pressure sensor is shown in Figure II-1 [5].

In the absence of external stress on the diaphragm (zero stress), the reinforcements are parallel. The resting capacitance C(0) is then given by [8] :

$$C_{(0)}=\varepsilon_0 \varepsilon_r \frac{A}{d} \qquad \text{II-5}$$

Where:

- ε_0 is the vacuum permittivity, approximately 8.86×10−12 F/m
- $\varepsilon_r$is the relative permittivity of the gas sealed within the cavity,
- A is the area of the fixed electrode,
- d is the distance between the two electrodes.

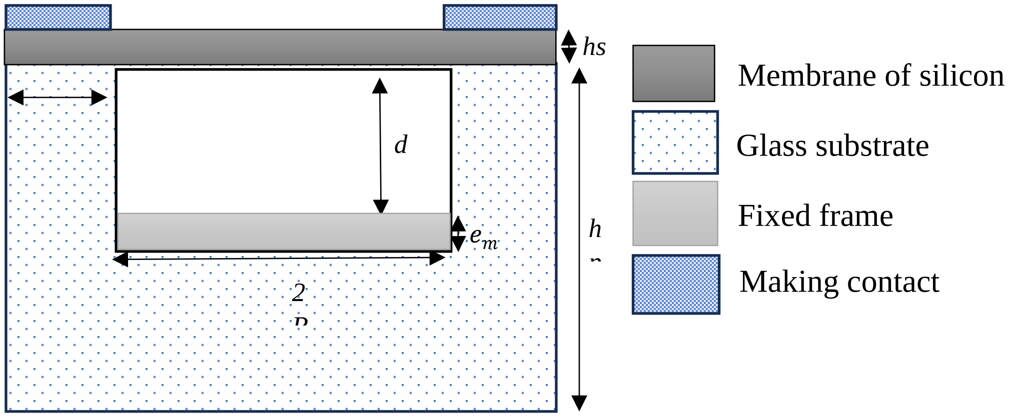

Figure II.1: Structure of a capacitive pressure sensor at rest

II.3.2 Capacitive Response C (P) (Capacitance Calculation)

When a pressure P_{ext} greater than the reference pressure is applied, the membrane deforms, resulting in a variation of the deflection $\mathrm{w}(x, y)$, as shown in Figure (II.2). This deflection, in turn, leads to an increase in the capacitance C(P) [6].

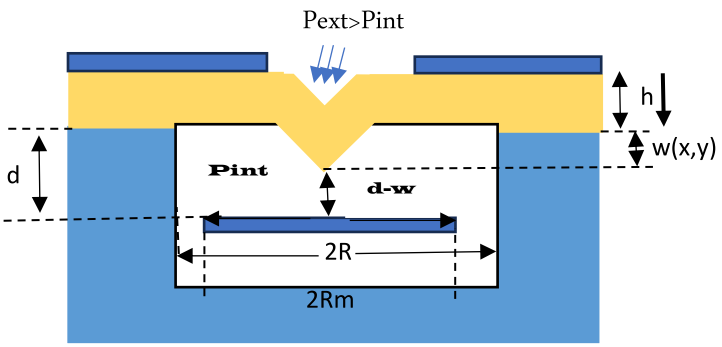

Figure II.2: Structure of the capacitive pressure sensor in operation

At equilibrium the expression of the capacity $\mathrm{C}(P)$ is expressed by the following relation:

$$\mathrm{C}\,(P_{ext} - P_{in}) = \varepsilon_0 \varepsilon_r \iint_A \frac{\partial A}{d - w(x,y)} \qquad \text{II-6}$$

w (x, y) is the deflection of the membrane at all points of a Cartesian reference frame whose center is the center of the membrane.

d – *w* (x, y) represents the variation between the two electrodes which varies at all points

Where ∂A represents a surface element of the fixed armature and *w* (x, y) the deflection of the membrane at all points of a Cartesian reference whose center is the center of the membrane.

For a circular membrane of radius R and in the case of small deflections (w<<h), the deflection w is given in cylindrical coordinates by [9]:

$$w(r) = \frac{12p(1-v^2)R^4}{64Eh^3}\left(1 - \frac{r^2}{R^2}\right)^2 \qquad \text{II-7}$$

Où P= [P_{ext} -P_{in}] is the differential hydrostatic pressure applied between the two faces of the membrane.

E: Young's modulus (130 GPa for silicon),

v: Poisson's ratio (0.28),

h: membrane thickness.

From equation (II-7), the membrane deflection w(r) can be decomposed into two parts: a part w(0) independent of the coordinates and another, w_n (r) independent of the pressure:

$$w(r) = w(0)w_n(r) \quad \text{II-8}$$

With $w_n(r)$ is the normalized deflection:

$$w(r) = \left(1 - \frac{r^2}{R^2}\right)^2 \quad \text{II-9}$$

$w(0)$ the deflection at the center of the membrane:

$$w(0) = \frac{3(1-v^2)S^4}{16\pi^2 E h^3} P \quad \text{II-10}$$

Where S is the surface area of the membrane.

The previous equation shows that the deflection at the center is directly proportional to the pressure. The sensor response to pressure P is then written [10]:

$$C(p) = \varepsilon_0 \varepsilon_r \int_0^{Rm} \int_0^{2\pi} \frac{1}{d-w(r)} dr d\theta = \varepsilon_0 \varepsilon_r I_1 \quad \text{II-11}$$

Where R_m represents the radius of the fixed frame.

Expanding the integral, I_1we obtain

$$I_1 = \frac{c(0)}{2\varepsilon_0 \varepsilon_r \gamma^2} \sqrt{\frac{d}{w(0)}} \ln \left[\frac{\frac{d}{w(0)} + \gamma^2 \sqrt{\frac{d}{w(0)} + \gamma^2 - 1}}{\frac{d}{w(0)} - \gamma^2 \sqrt{\frac{d}{w(0)} + \gamma^2 - 1}} \right] \quad \text{II-12}$$

$$\gamma = \frac{R_m}{r} = \sqrt{\frac{A}{s}} \quad \text{II-13}$$

In the quasi-linear regime (w(0) <<d), we can develop the previous equation in Taylor series. The integral is then approximated by [11]:

$$I_1 \approx \frac{C(0)}{\varepsilon_0 \varepsilon_r} \left[1 + \frac{w(0)}{d} \psi\right] \quad \text{II-14}$$

With:

$$\psi = \frac{1-(1-v^2)}{3\gamma^2} \quad \text{II-15}$$

An effective deflection can then be defined as:

$$W_{eff} = \psi w(0) \tag{II-16}$$

For γ = 1, the relationship can be simplified by:

$$I_1 \approx \frac{c(0)}{\varepsilon_0 \varepsilon_r}\left[1 + \frac{W_{eff}}{3d}\right] \tag{II-17}$$

The response of the approximate sensor capacity can then be put in the following form:

$$\mathrm{CL(P)} \approx \mathrm{C(0)}\left[1 + \frac{w(0)}{3d}\right] \approx \mathrm{C(0)}\left[1 + \frac{W_{eff}}{d}\right] \tag{II-18}$$

From expression (II.18) we deduce the value of the capacitance C (P) at any point of the sensor [6]:

$$\mathrm{CL(P)} \approx \mathrm{C(0)}\left[1 + \frac{(1-v^2)}{16E}\frac{R^4}{h^3}\frac{P}{d}\right] \tag{II-19}$$

II.4. Sensitivity

The sensitivity to the applied pressure is defined as the rate of change of the capacitance with respect to pressure, expressed as[7][12]:

$$S_P \approx \frac{\partial c}{\partial P} \tag{II-20}$$

By substituting the analytical expression of the capacitance C(P) into Equation (II-20), an exact expression for the pressure sensitivity of a circular-shaped membrane can be obtained, given by:

$$S_P \approx \frac{\partial c}{\partial P} \approx \frac{C(0)}{d}\frac{R^4}{h^3}\frac{(1-v^2)}{16E} \tag{II-21}$$

where:

- $C(0)$: the initial capacitance at zero pressure,
- d: the initial gap between the membrane and the fixed electrode,
- R: the radius of the circular membrane,
- h: the membrane thickness,
- v: Poisson’s ratio of the membrane material,
- E: Young’s modulus, representing the material’s elasticity.

II.5. Electronic Conditioning of the Capacitive Pressure Sensor (Sensor Linearization)

Some sensors exhibit a nonlinear response, often with a well-defined nonlinearity pattern. Rather than relying solely on multiple calibration points and interpolation, it is generally more effective to apply a systematic linearization method to correct this inherent error. For instance, sensors with a logarithmic transfer characteristic require appropriate compensation to ensure accurate and reliable measurements.

A logarithmic transfer curve can be easily linearized using an electronic circuit with an exponential transfer function (Figure II.3). One possible approach is to exploit the exponential relationship between the base-emitter voltage and the collector current of a bipolar junction transistor (BJT). In this configuration, the sensor output signal is a voltage, and the collector current is converted into an output voltage using a current-to-voltage converter, forming the overall transfer function of the sensor and the conditioning circuit [].

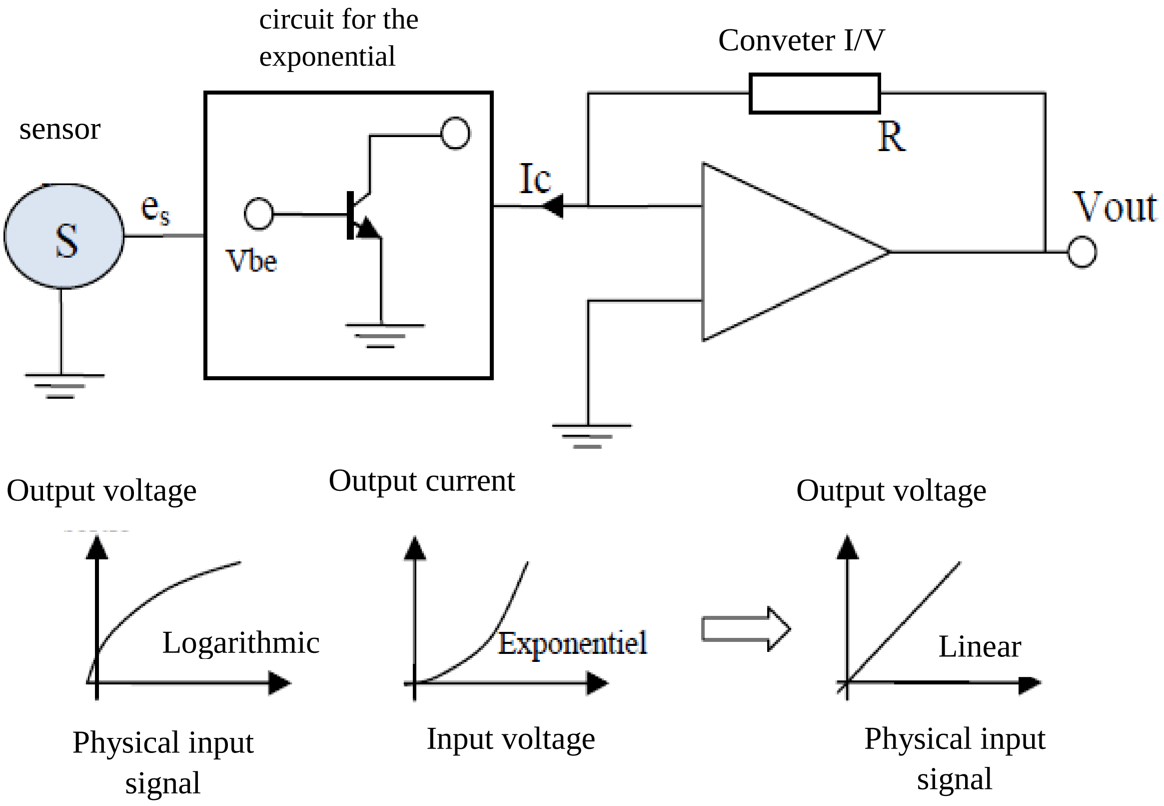

Figure II.3: Sensor Characteristic Linearization

II.5. Conclusion

Based on the relationship between sensitivity and design parameters, it can be said that achieving high sensitivity in a capacitive pressure sensor requires three key conditions:

First, the membrane should have a large surface area, as this allows it to interact more effectively with pressure changes.

Second, the distance between the electrodes must be small, so that even slight pressure variations cause noticeable changes in capacitance.

Third, the membrane should be very thin, enabling it to respond easily to minimal pressure. With these conditions met, the sensor can deliver more accurate and efficient pressure measurements.

Finally, sensor linearization is achieved through the proposed conditioning circuit.

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Chapter III:

Design, Optimization, and Electronic Conditioning of the Pressure Sensor

III.1. Introduction

The design and performance optimization of a MEMS (Micro-Electro-Mechanical System) capacitive pressure sensor requires knowledge of the mechanical behavior of the test body as a function of pressure, and the determination of well-specified geometric parameters for sensor construction.

In this chapter, we focused on the structural design and optimization of the capacitive pressure sensor to improve sensitivity and linearity, and subsequently define the technological parameters of the pressure sensor. We studied the mechanical behavior of a thin, circular silicon membrane, perfectly embedded at the edges, subjected to a uniform and constant pressure using MATLAB software, which allowed us to locate the most deformable points of the membrane.

We then studied the simulation of these devices to determine the influence of each parameter on their sensor response. To validate our results, we simulated our structure using COMSOL Multiphysics software.

We then analyzed the sensor in a developed conditioning circuit using the PSPICE simulator. This simulation allowed us to evaluate the sensor's conditioning.

III.2. Results and Discussions

This study analyzes the operation of a capacitive pressure sensor designed to measure blood pressure between 0 and 300 mmHg, used in biomedicine. First, we modeled the mechanical behavior of the sensor membrane using analytical equations describing its deformation under applied pressure, which allowed us to monitor how the capacitance changes with pressure. Next, we investigated how three important geometric parameters the membrane surface area, its thickness, and the distance between electrodes influence the sensor's sensitivity.

III.2.1. Effect of Membrane Thickness on Deflection

In this section, we studied the effect of certain geometric and mechanical parameters of the capacitive sensor on membrane deflection under the effect of applied pressure.

From the expression (II-7), we plotted the variation curve of the deflection at the center of the membrane, w(r), as a function of different values of the thickness h.

The simulations were performed using the physical properties of silicon, a material commonly used in microfabrication, with the following values:

E: Young's modulus (130 GPa for silicon),

ν: Poisson's ratio (0.28),

h: membrane thickness (11 µm, 13 µm, 15 µm, 17 µm).

This analysis allows for a better understanding of the influence of thickness on the pressure sensor's sensitivity, as the membrane influences its mechanical flexibility.

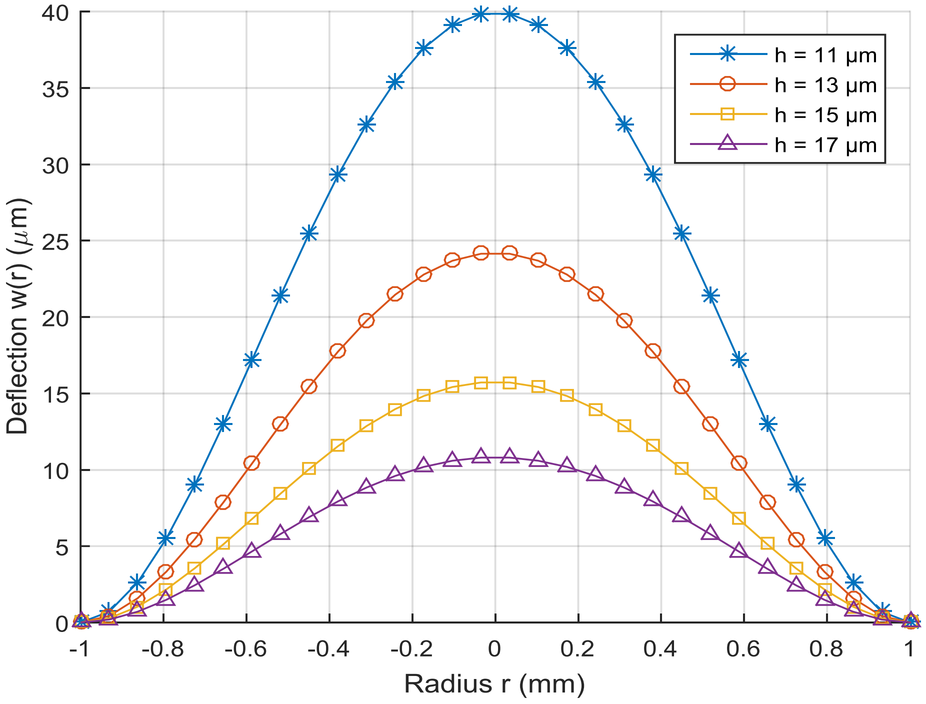


Figure.III.1: Membrane deflection as a function of radius r, for different h and P=4*$10^4 Pa$

Figure III.1 shows the deflection of the silicon membrane as a function of the radius r, for different thicknesses h (11 µm, 13 µm, 15 µm and 17 µm), under a constant applied pressure $P=4*10^4$ Pa.

The results show that the maximum deflection at the center of the membrane d (40 µm, 24 µm, 16 µm and 11 µm), respectively, decreases with increasing thickness. Indeed, a thicker membrane has increased mechanical rigidity, thus limiting its deformability under pressure. This variation in deflection has a direct influence on the effective distance between the electrodes of the capacitive sensor, a determining parameter for sensitivity. This analysis is crucial to define the optimal pressure operating range of the microsystem, estimated here at less than $4*10^4$ Pa, in order to guarantee a linear response, without contact or saturation, meeting the precision requirements in biomedical applications.

III.2.2. Rest Capacitance C (0)

The resting state of a capacitive pressure sensor is characterized by zero differential pressure (ΔP = Pext - Pint = 0). Figure (III.5) illustrates the variation of the resting capacitance, C(0), as a function of the electrode surface area (A) for different values of the interelectrode distance (d).

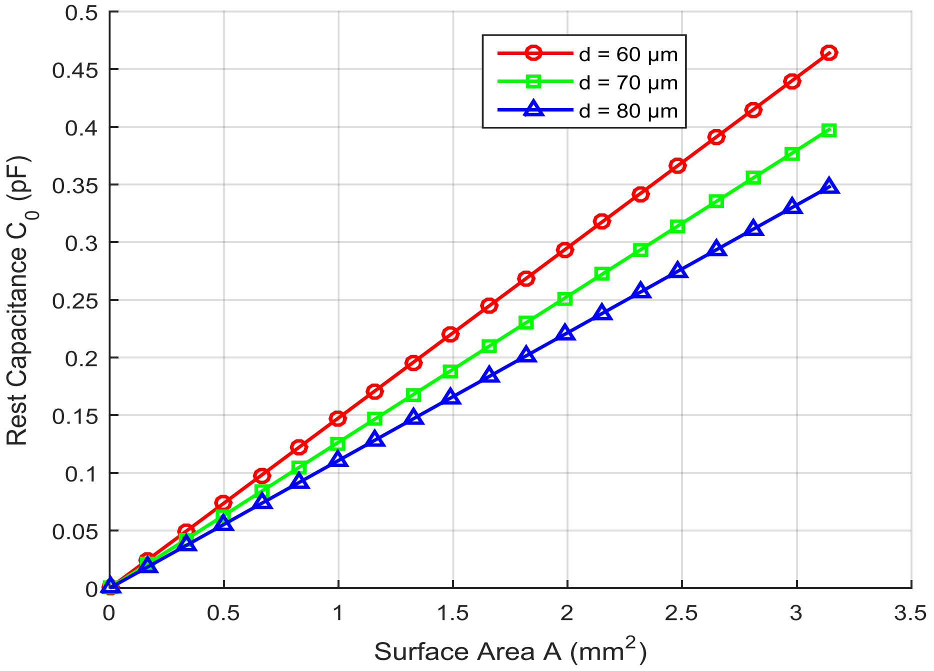


Figure.III.2: The resting capacity C(0) as a function of the surface area (A) for (d) different

Figure III.2 illustrates the influence of the geometric parameters of the membrane on the resting capacitance of a capacitive pressure sensor. Note that increasing the surface area (A) gives an increase in the resting capacitance C(0), while increasing the interelectrode distance (d) induces a decrease in this capacitance C(0).

III.2.3. Capacitive response C(p)

From the analytical expression (II-19) describing the response of a capacitive pressure sensor, we plotted curves representing the variation of capacitance as a function of the applied pressure Pext on a circular membrane.

In this case, we set the membrane radius to r = 1 mm and we plotted the capacitive pressure response curve of the sensor for different values of interelectrode distance (d), as well as for different membrane thicknesses h (11 µm, 13 µm, 15 µm, 17 µm). The result is shown in Figure III.3.

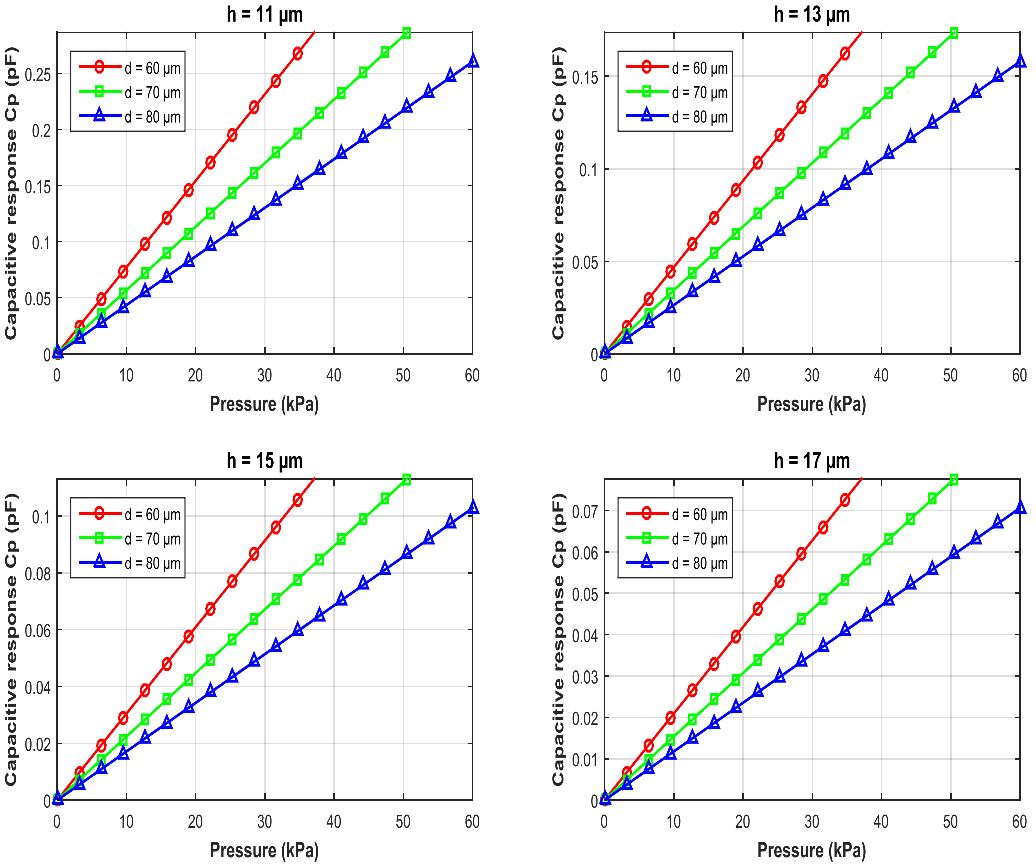


Figure.III.3: Capacity as a function of pressure at thickness h=11µm, h=13µm, h=15µm, h=17µm, for (d) different

It is observed that the capacitance varies linearly with the pressure applied to the membrane for different interelectrode distances (d). Analyzing several membrane thicknesses, namely h = 11 µm, 13 µm, 15 µm, and 17 µm, it is observed that the sensor's sensitivity decreases slightly with increasing thickness. This shows that thinner membranes improve the capacitive response to pressure.

Figure III.3 also shows that the sensitivity is higher when the membrane thickness is thin, especially for h = 11 µm.

III.2.4. Effect of Geometric Parameters on Sensor Sensitivity Sp

To analyze the influence of geometric characteristics on capacitive sensor performance, we studied the variation in sensitivity as a function of several fundamental structural parameters.

Based on the analytical expression of capacitance C(p) as a function of applied pressure, we generated curves illustrating the evolution of sensitivity for different values of electrode surface area (A), inter-electrode distance (d), and membrane thickness (h). This parametric study quantifies the effect of each geometric dimension on the sensor's capacitive response.

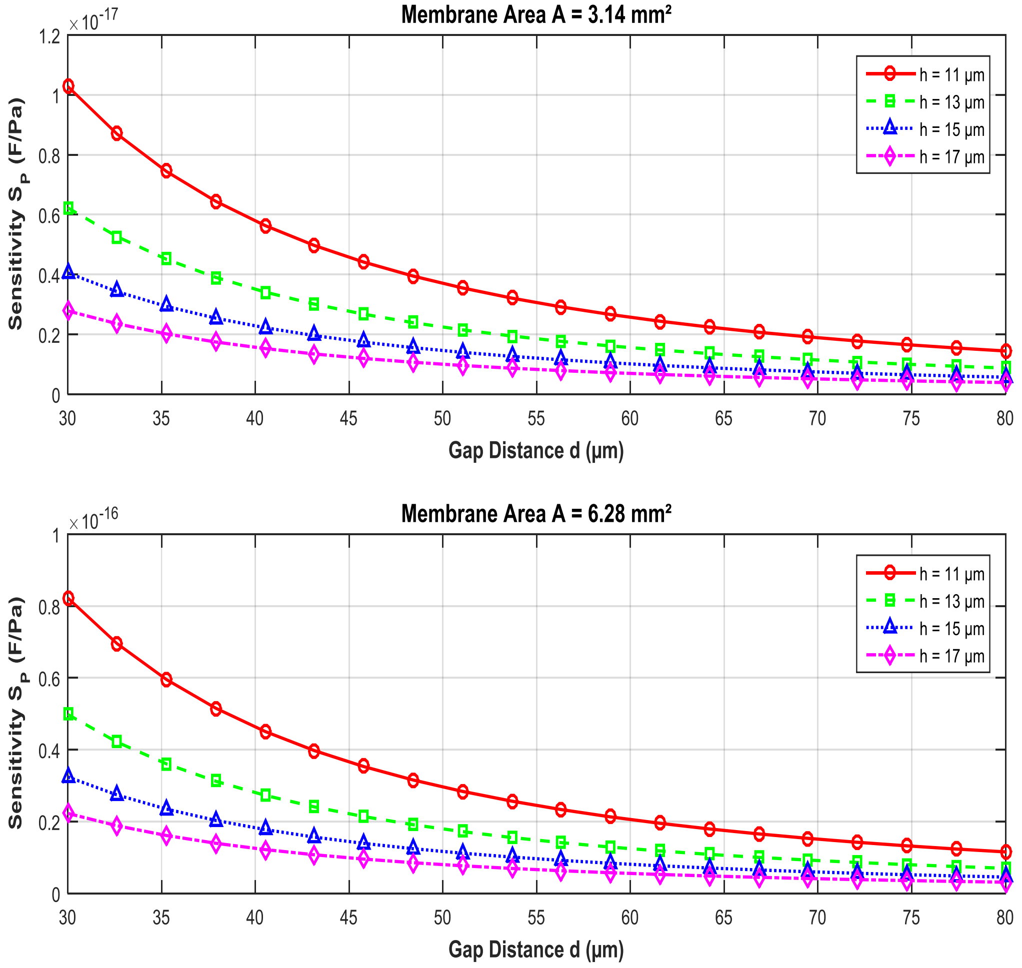


Figure.III.4: Sensor sensitivity as a function of (d) for a surface: (a)A= 3.14mm^2, (b)A= 6.28mm^2.

The results obtained reveal clear trends: increasing the surface area significantly improves sensitivity, while increasing the distance between the electrodes or the membrane thickness results in a significant decrease in sensitivity. These observations are consistent with the expected physical behavior of the device and are discussed in detail in Figures III.4 (a) and III.4 (b)

These results show that sensor geometry has a direct impact on its sensitivity. It is therefore essential to choose it carefully for applications requiring high accuracy.

III.3. Sensor simulation using Comsol Multiphysics software

III.3.1. Comsol Software Overview

Comsol Multiphysics, formerly known as FEMLAB, is primarily a tool for solving partial differential equations using finite elements. Its unique feature is its database of equations that can be used to model various physical phenomena, such as electrostatics, as well as multiple physical phenomena modeled using PDEs (partial differential equations). Initially developed as a MATLAB toolbox, it now has its own graphical environment that allows both drawing geometries and displaying post-processing results. Its unique feature is also its ability to couple different PDEs (partial differential equations) to describe multiphysical phenomena, making it particularly suitable for microelectronics. For example, it is possible to obtain the deformation of a membrane due to pressure in a liquid, or the temperature rise in a conductor due to the passage of an electric current. Advanced functions allow the manual entry of specific PDEs (partial differential equations). In addition, the software data is accessible from Matlab, which allows for scripting [1,2].

III.3.2 Design Parameters

Device design depends on various parameters such as material, structure, and shape. All parameters must be optimized to achieve the desired device specifications. The design began with the selection of the substrate material and its properties [3]. In this work, silicon (100) with a Young's modulus of 130 GPa and a Poisson's ratio of 0.28 was used. Silicon was chosen for its high melting point, low coefficient of thermal expansion, low mechanical hysteresis, etc. Based on these properties, the membrane shape was optimized. All parameters required for the design of capacitive pressure sensors were optimized for this shape. The analysis is performed using 3D space dimension, structural mechanics module, structural mechanics, solid stress-strain, and static analysis.

Table III.1: Optimized dimensions of silicon membranes

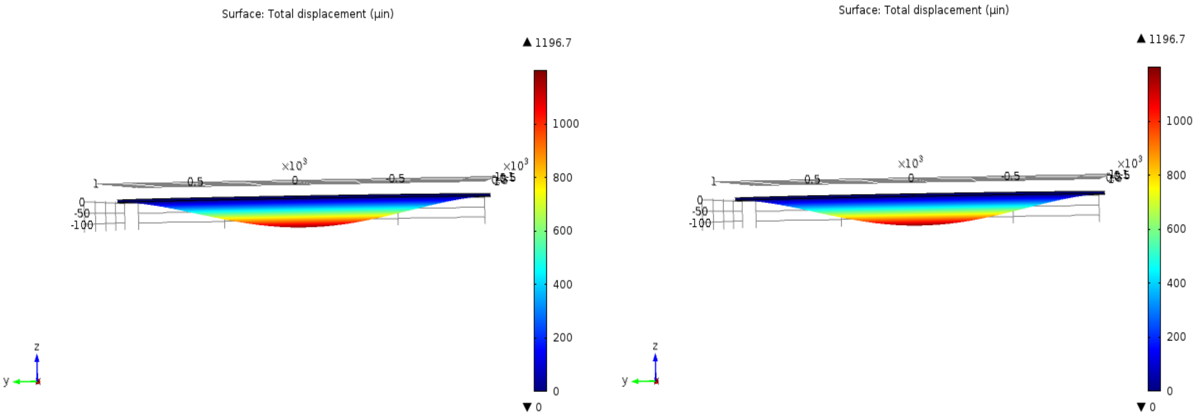
Parameters	**Values**
Ray (R)	1mm
thickness of the membrane (h)	11µm, 13µm, 15µm, 17µm
Young's modulus (E)	130 GPa
Poisson's ratio (v)	0,28

The pressure applied to the membrane surface at a value $P=4*10^4$pa

III.3.3. Result of the simulation

The pressure capacitor is composed of silicium circulatory plaques as a condenser with the air as electrical plaques. The superior plaque is a deformable membrane and the inferior plaque is a fixed electrode. When the pressure is applied to the superior plaque it reforms and changes the distance between the condensate plaques. This capacitance variation can also be observed to detect the applied pressure. The deformation of the membrane after the simulation is repeated on the figure III.5.

h=11um **h=13um**



h=15um **h=17um**

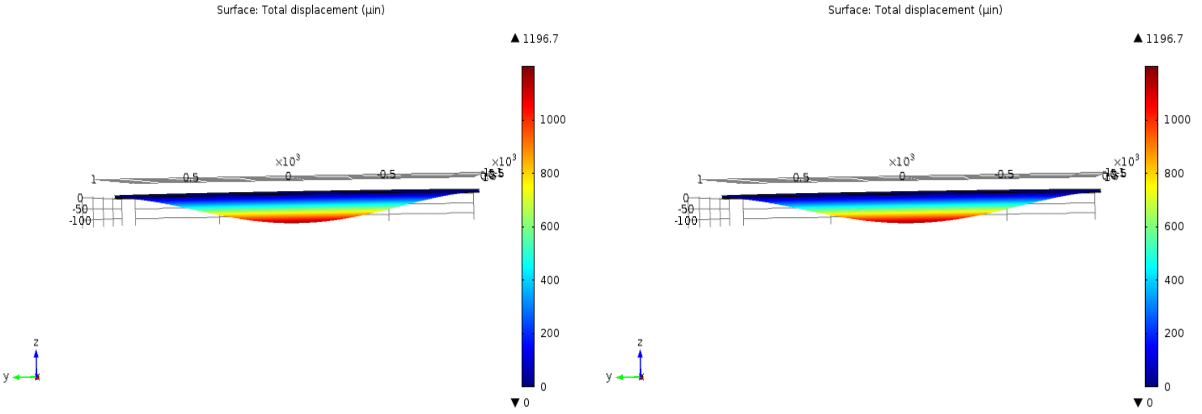
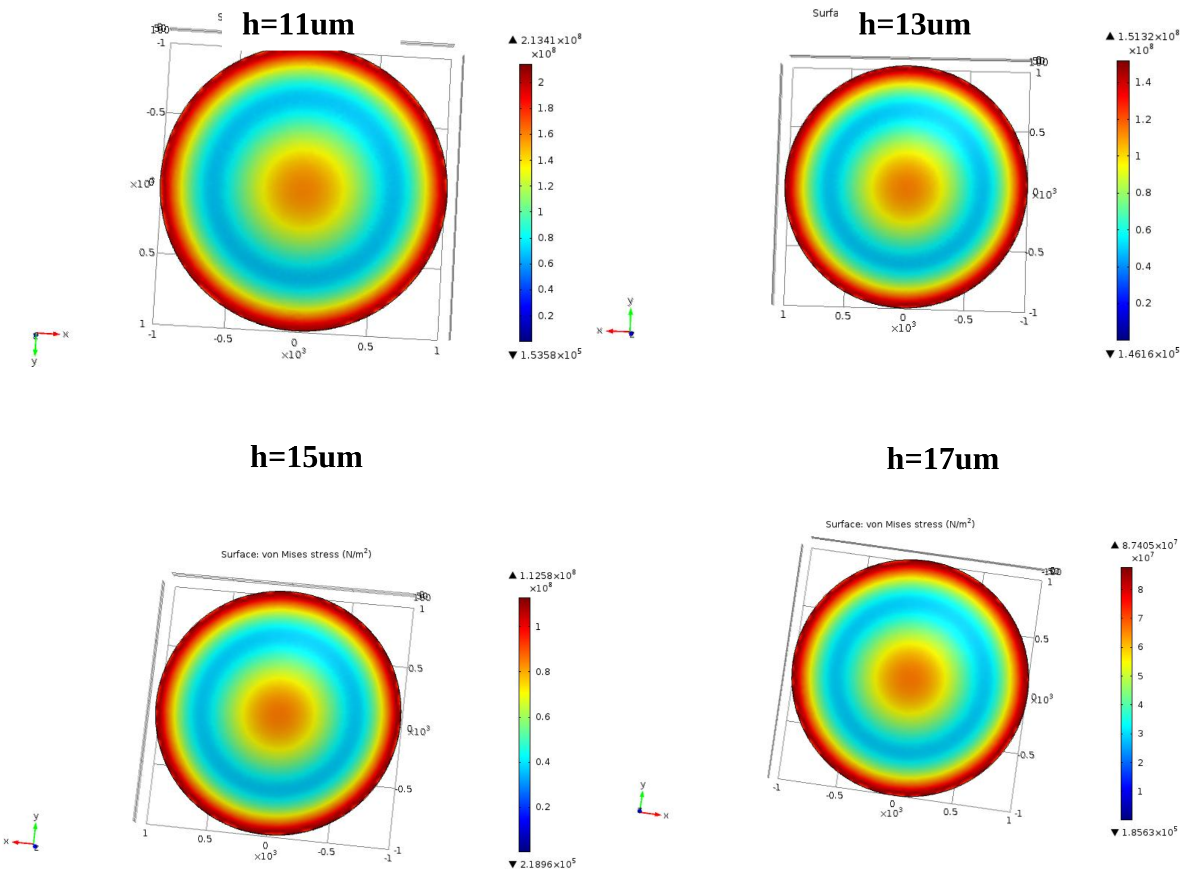


Figure III.5: Deflection of a Circular Membrane for Thicknesses h = 11 µm, 13 µm, 15 µm, and 17 µm.

Figures III.5 represent the 3D deflection of a circular capacitive pressure sensor membrane with a radius R = 1 mm, a thickness (h = 11 µm, h = 13 µm, h = 15 µm, h = 15 µm), and an applied pressure of 40KPa.

These figures show that the deflection at the center of the membrane is directly proportional to the applied pressure. Note that the maximum deflection occurs at the center of the membrane.

It is of order (1196.7um;1.5132um;1.1258um;8.7405um), so the thicker the membrane, the less distortion there is at the center of the membrane and the greater the stress at the edges of this membrane. This model allows us to validate the results we obtained using Matlab.


h=11um

h=13um

h=15um

h=17um

Figure III.6: Stress in a Circular Membrane for Thicknesses h = 11 µm, h = 13 µm, h = 15 µm, and h = 17 µm.

III.4. Analysis of the Capacitive Pressure Sensor by the SPICE Simulator

Simulation is a very important step in the design of analog circuits. It allows us to observe optimized results at a lower cost. Evaluating the performance of a circuit with SPICE software.

The quality of the results obtained from the design and simulation of electronic circuits depends on the accuracy of the models used [4]. In this context, we propose a circuit model for conditioning the capacitive pressure sensor using the SPICE simulator, which will allow us to test the performance of the capacitive pressure sensor circuit model.

III .4.1 Presentation of the SPICE simulator

SPICE (Simulation Program with Integrated Circuit Emphasis) is a software program developed by the University of Berkeley in the United States (http://www.eecs.berkeley.edu) in the 1970s in FORTRAN. It is a standard electrical simulator that allows static and transient analysis of nonlinear circuits and small-signal AC analysis of linearized circuits. Circuits simulated by the SPICE simulator can contain numerous electronic elements: resistors, capacitors, inductors, mutual inductors, transmission lines, distributed RC lines, controlled and independent voltage and current sources, switches, as well as models of active devices such as diodes, bipolar transistors, junction field-effect transistors (JFETs), gallium arsenide (GaAs or GaAs) metal-semiconductor field-effect transistors (MESFETs), and metal-oxide-semiconductor (MOS) field-effect transistors. SPICE is therefore primarily a simulation software for analog electronic components and circuits, which has become a mixed-mode simulation in its most advanced versions. The models used to simulate components are derived from the physics of the components, and their parameters are most often physical parameters. Indeed, each component has a specific behavior described by a set of equations and parameters. These models, based on physics and measurement (Figure III.7), are relatively complete and realistic, which allows reliable simulations. They are placed in libraries. However, it is possible to create, modify a model associated with a component or add models that are distributed by most electronic component manufacturers [4].

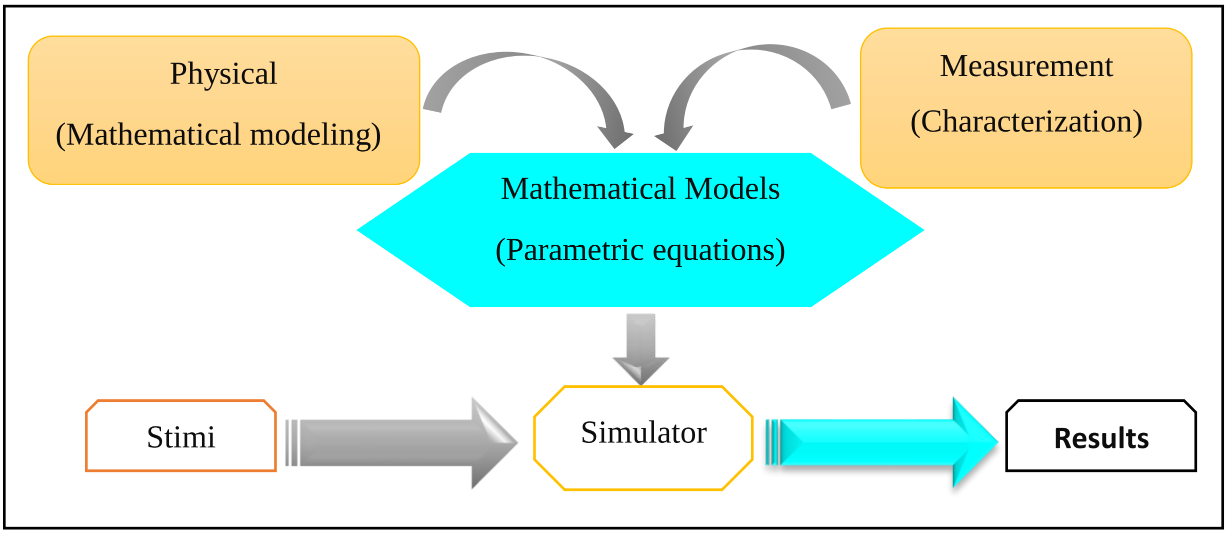


Figure III.7: Functional representation of SPICE [4].

Originally designed for analyzing electronic circuits in direct current (DC), alternating current (AC), and transient conditions. We used the 9.2 Demo version downloaded from the PSPICE website.

III.4.2. Electronic Conditioning Circuit Simulation

First, we placed the capacitive pressure sensor in a simple circuit, composed of a bipolar transistor and a resistor as an I/V converter, the goal is to represent the pressure sensor as a capacitance. The pressure sensor is characterized by the variation of the capacitance as a function of the applied pressure.

Then we set the temperature to 27°C (T=27) and varied the pressure in a range from 0 to , by the analysis "AC Sweep/Noise Parametric Sweep, Global Parameter" and the frequency of 50kHz "AC Sweep/Noise Logarithmic", we obtain the result shown in Figure II.3.

In order to be able to modify the functionality of the model before validating it, it is necessary to declare the constant terms (such as the surface area (A), the inter-electrode distance (d), the membrane thickness (h), the membrane radius (R), the Young's modulus (E), the Poisson's ratio (v)) as parameters using the (**SPICE / PLACE OPTIMIZER PARAMETERS**) instruction. These parameters are accessible for possible modification directly from the **PARAMETERS** section in Figure III.8.

The capacitive pressure sensor conditioning circuit model is schematically represented by the functional assembly shown in Figure III.8:

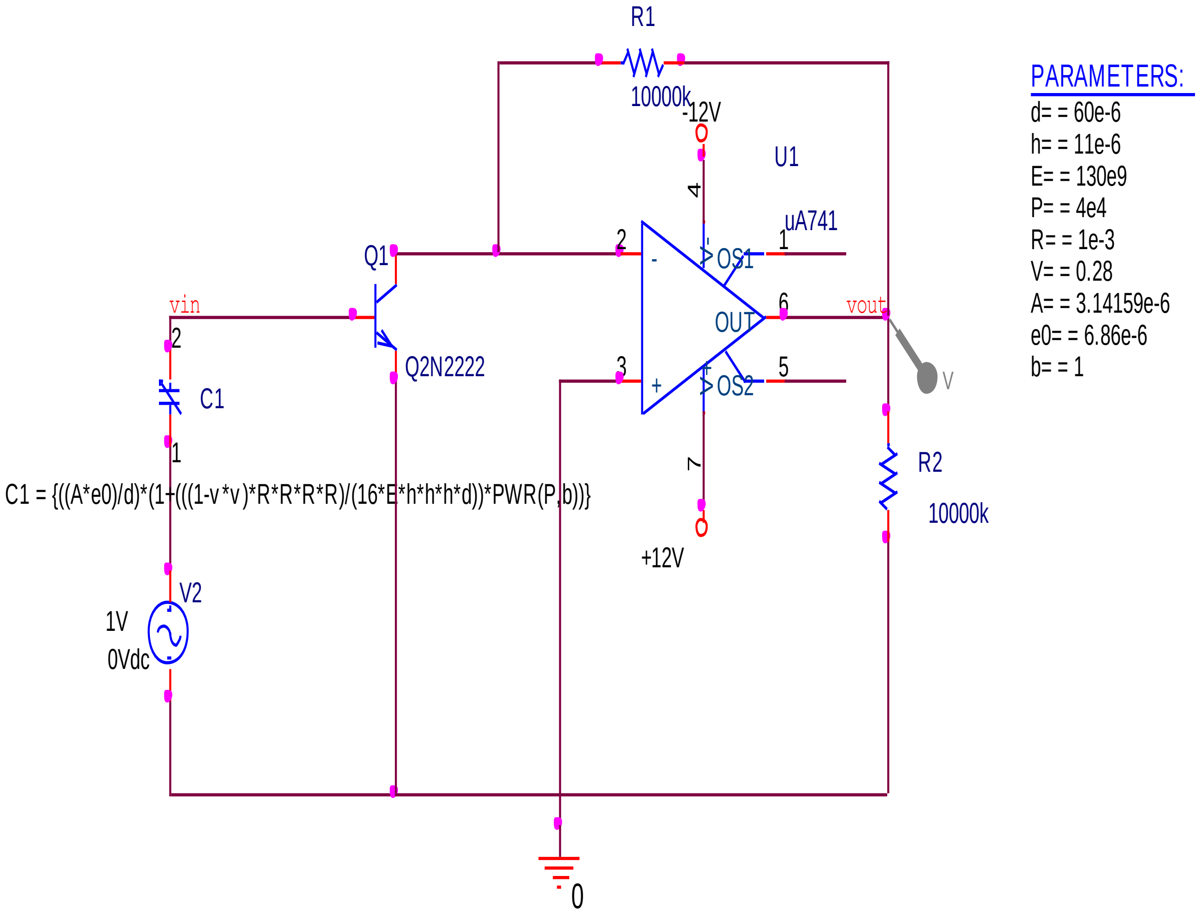


Figure III.8: PSPICE environmental conditioning circuit.

III.4.3 Pspice Simulation Results

To test the capacitive pressure sensor in an electrical environment, it was introduced into the conditioning circuit. We plotted the variation of the output voltage (V_{out}) and the capacitance as a function of the applied pressure.

III.4.3.1 Output Voltage as a Function of Pressure

The measured conditioning circuit output voltage of this sensor is plotted in Figure III.9. This figure represents the variation of the output voltage (V_{out}). as a function of the applied pressure.

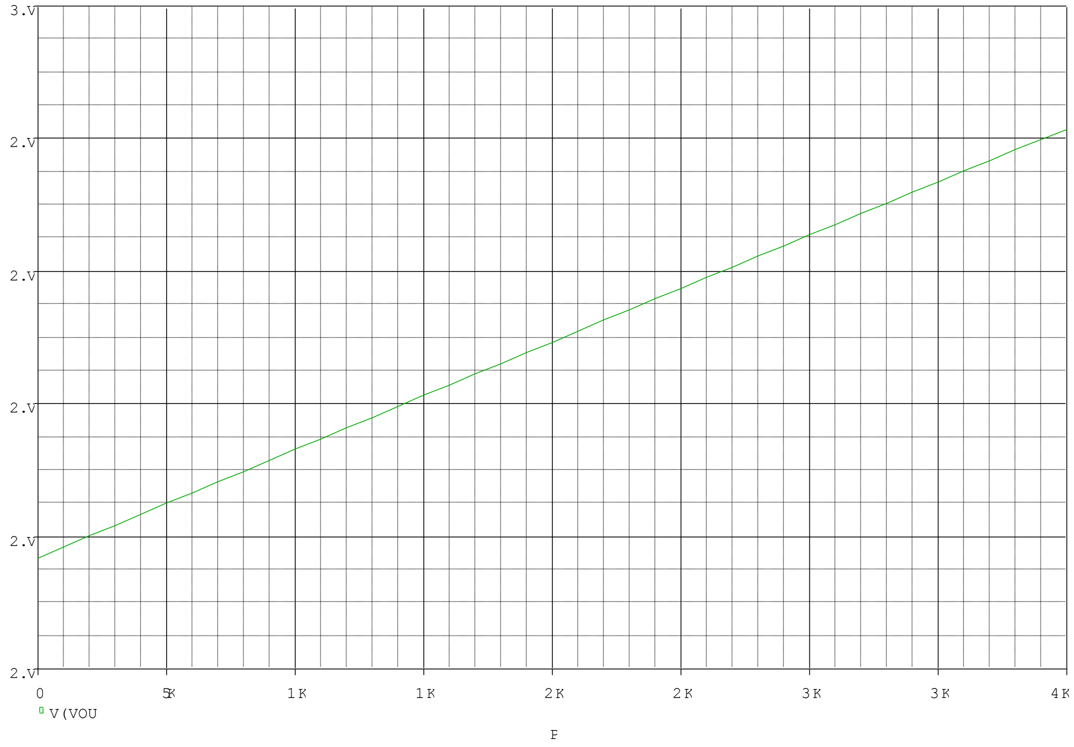


Figure III.9: Output voltage (V_{out})as a function of applied pressure P.

We note that:

- The output voltage (Vout) is linear as a function of the applied pressure.
- The increase in output voltage is directly proportional to the increase in applied pressure.
- For a pressure of 40 kPa, the sensor circuit voltage (Vout) has a value of 2.82 V.

III.4.3.2 Sensor Capacitance as a Function of Pressure

From the sensor conditioning circuit diagram, the resistance of the capacitance (called capacitive reactance) is defined by the relationship:

$$X_C = \frac{1}{2\pi f\, C(P)} = \frac{V_2}{I_C} \qquad \text{III.1}$$

Xc: capacitive reactance in ohms.

f: is the frequency in Hertz [Hz].

Therefore, the capacitance relationship is equal to:

$$C(P) = \frac{I_C}{2\pi f V_2} \qquad \text{III.2}$$

Figure III.10 illustrates the response of the capacitive pressure sensor as a function of the applied pressure.

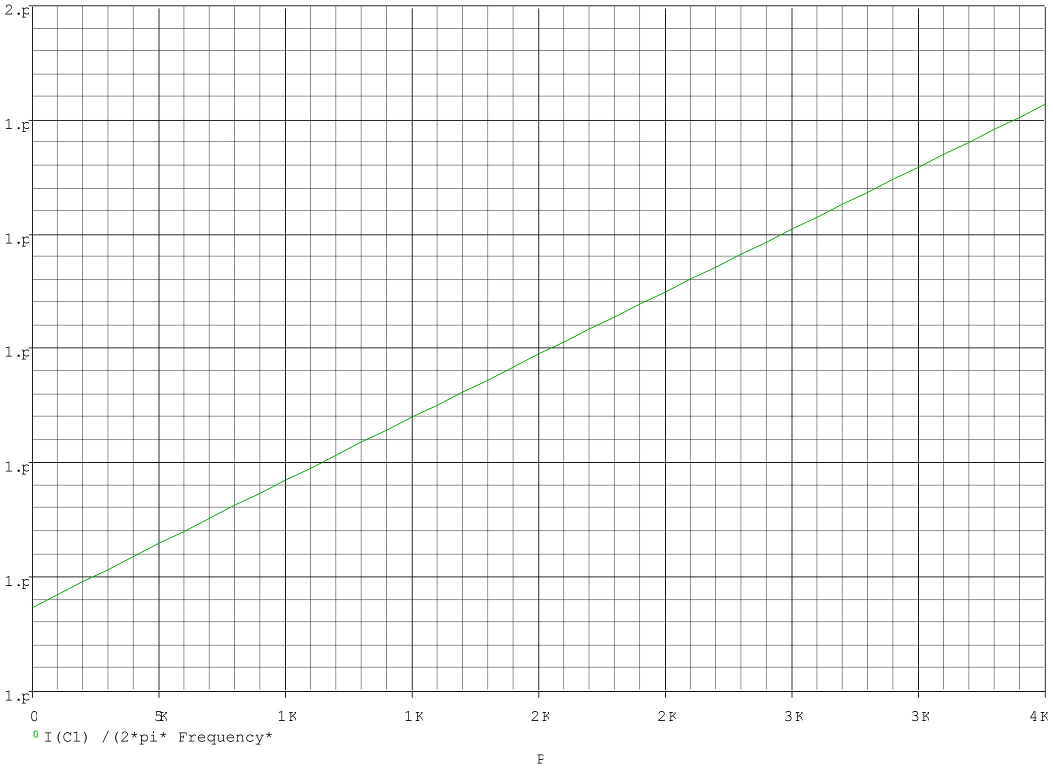


Figure III.10: Variation of capacity as a function of pressure.

We note that:

- The variation in capacitance is a linear function of the applied pressure.
- For zero external pressure ($P = 0$). the sensor capacitance C (P)=C_0.
- For a pressure range from 0 to $P = 40\text{kPa}$, the sensor capacitance varies by the relationship C (P)=$I_C/(2\pi f V_2)$.

III.5. Conclusion

In this work, we modeled and simulated the behavior of a capacitive pressure sensor. Based on the developed analytical model, we studied the membrane deformation under applied pressure using MATLAB. The results showed that the central deflection of the membrane increases proportionally with the applied pressure, leading to a variation in the sensor's capacitance.

We then analyzed how geometrical parameters such as membrane thickness, electrode gap, and membrane surface area influence the sensor's capacitance and sensitivity. The simulations carried out with COMSOL Multiphysics confirmed the MATLAB results, validating our approach.

Improved sensitivity was achieved by optimizing specific parameters: a well-selected membrane surface area ($A=3.14\ mm^2$), a cavity thickness of 60 μm, and a membrane thickness of 11 μm.

Finally, based on the conditioning circuit modeled and simulated using PSPICE, we observed that both the output voltage and the capacitance vary linearly with the applied pressure. This confirms the performance and reliability of the proposed sensor design.

Bibliographic References for Chapter III

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General Conclusion

In conclusion, this study demonstrates the growing importance of microelectromechanical systems (MEMS) pressure sensors in various fields, particularly in medical and industrial applications. These technologies have proven their ability to provide accurate and efficient measurement solutions, contributing to the advancement of automation, control, and monitoring. Various types of pressure sensors are reviewed, with a focus on capacitive sensors, which are characterized by their high sensitivity and stability. The theoretical and practical aspects related to modeling these sensors are also highlighted, including membrane deflection analysis, capacitive response calculation, and sensitivity determination. It is shown that geometric parameters such as membrane area, thickness, and electrode spacing play a critical role in determining sensor performance.

Furthermore, we presented a model describing the mechanical behavior of a thin silicon membrane with a circular shape, perfectly clamped at the edges, and derived the expressions for its deflection. Based on this, we introduced a theoretical model of a capacitive pressure sensor using a circular membrane, both at rest and under static pressure conditions, as a function of the device's geometric parameters. Using the expression of the capacitive response C(p) as a function of the applied pressure, we were able to determine the pressure sensitivity model of the sensor.

Subsequently, we analyzed the mechanical behavior of the same membrane under uniform and constant pressure using MATLAB software. The results showed that the maximum deflection at the center of the membrane is directly proportional to the applied pressure, allowing us to identify the most deformable regions. Finally, we simulated the sensor structures to evaluate the influence of each parameter on their response. To validate our results, we conducted a final simulation of the sensor model using COMSOL Multiphysics.

Finally, the simulation of the conditioning circuit using PSPICE showed that both the output voltage and the capacitance change linearly with the applied pressure. This linear relationship confirms the efficiency and reliability of the proposed sensor design.