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Thermo mechanical modeling of piezoresistive pressurs sensor using FDM of Electric heater

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Dedication

I dedicate this modest work to:

- My dear parents.
- My dear brothers.
- My Family and all my Loved Ones.
- All my friends.

Maarad Takiyeddine

I dedicate this modest work to:

- My dear parents.
- My dear brothers.
- My Family and all my Loved Ones.
- All my friends.

Meddour Younes

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General Introduction

General Introduction:

The need to automate certain processes in such varied fields as thermodynamics, aerodynamics, acoustics, fluid mechanics, biophysics, medicine, etc. pushes us to introduce more and more sensors of all kinds. In particular, one distinguishes the pressure sensor, which constitutes most of the market for MEMS devices. It is a device that essentially transforms a physical quantity, the object of the measure, called the measurende, into another physical quantity, generally an electrical image of the input quantity [1].

In this type of sensor, there are several ways to detect the deformation of a diaphragm under uniform and constant pressure. The most obvious is to determine the deflection of the membrane by exploiting the silicon piezoresistivity for the piezoresistive type sensor or by using the change in capacity for the capacitive type [2-3].

As market demands for pressure sensor performance become increasingly demanding, research is directed towards their optimization and design by treating the various parameters that influence the proper functioning of these devices. Several attempts at improvements have been made to achieve the optimum conditions for the ideal operation of these sensors.

Given the importance of the role played by this device, it is therefore essential to optimize its performance by minimizing its temperature drift. It is in this context that this thesis work, which was devoted to the modeling and thermomechanical simulation of silicon pressure sensors, is taking place.

The development of a suitable device is a difficult undertaking due to the complexity of its design and the optimization of its performance. The sensor manufacturing process requires an evaluation of their response to a simulated scenario, thus avoiding costly experimentation processes. Virtual prototyping models and tools can simulate various parameters and analyze the phenomenon of temperature dependence. It becomes essential to integrate all relevant phenomena within the system, even if this implies a complicated coupling analysis. The success of a sensor project relies heavily on the optimization phase, which involves performing simulations on advanced software. These programs make it possible to carry out extensive simulations in a limited amount of time and also estimate the influence of technological processes on sensor performance. To carry out this work, we propose to contribute to the improvement of their performance by proposing models that predict the mechanical and thermal behavior of pressure sensors by minimizing the effect of temperature by optimizing their geometric parameters.

This manuscript is structured into three chapters.

The first chapter is devoted to the study of piezoresistive and capacitive pressure sensors, explaining their main characteristics, performance, design, and manufacturing techniques. Then, a bibliographical summary on sensors, microcensors, and MEMS describes the main work already done in this field.

In the second chapter, we will explain the main theoretical foundations necessary for understanding the principle of operation of these devices and their main characteristics. Subsequently, we will establish a piezoresistif pressure sensor model under the COMSOL Multiphysics environment that takes into account the entire structure of the piezoresistif pressure sensor. This model makes it possible to study the maximum deflection at the center of the membrane and the normal stresses acting on its edges as a function of pressure.

The third chapter is devoted to the elaboration of a numerical model governing the propagation of heat in piezoresistance in cartesian coordinates for the variable regime and its resolution by the method of finite differences. The results obtained make it possible to predict and optimize the thermal drift generated by the Joule heating effect in piezoresistive pressure sensors. The established model allows, on the one hand, to examine the effect of the bridge bias voltage, the operating time of these devices, and the influence of their geometric parameters on the generation of heat.

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Chapter I:

State of the Art of pressure sensors

I.1.Introduction:

Piezoresistive and capacitive sensing pressure sensors are two common types of pressure sensors that are used to measure pressure changes in various applications. Pressure sensors, using piezoresistive or capacitive principles, have widespread applications in various industries. Silicon, due to its properties, is the primary material used for MEMS devices, including pressure sensors. These sensors constitute the largest segment of the MEMS market, with increasing demand for high-performance devices [1].

The goal is to create piezoresistive and capacitive pressure sensors by measuring the deformations of a proof body and converting them into electrical signals. MEMS technology has revolutionized pressure sensors through miniaturization, reducing the number of parts and assemblies. This has resulted in smaller and more efficient sensors. The development of MEMS and digital technology has brought about a revolution in sensors - the emergence of intelligent sensors. These sensors integrate the sensor, actuator, associated electronics, and digital parts on a single chip. This allows for modifications to the sensor's behavior and local processing and calculations to optimize data collection [2].

I.2.History:

In 1954, Smith made the piezoresistive effect discovery. The fluctuation in resistivity of a germanium or silicon substance under varying mechanical forces is represented by this phenomenon. He found that the deformation of the energy bands, which results in the changing of the material's resistivity under mechanical stress, is the primary cause of the modification of resistance in semiconductors [3].

In 1982, Using the finite difference technique, Wise created a model to calculate membrane deflection as a function of pressure and temperature. The performance of the piezoresistive pressure sensors was then optimized after he evaluated their thermomechanical response. Through this effort, the sensor's thermal sensitivity was decreased throughout a narrower temperature range (-30 to 70°C).

In 1995, Elgamel created a semi-analytical method to enhance an earlier technique for calculating the deflection of a membrane under pressure. Using Hooke's rules, the model calculates the constraints and finds the deflection for significant deformations. The model simply takes into account the ambient temperature and has limitations when it comes to reproducing temperature variations and coupling other physical phenomena for accurate simulation of sensor response [4].

In 1998, Chauffeur developed a finite element model in the ANSYS environment to model the thermomechanical behavior of pressure sensors. The model included the coupling of three physical phenomena: thermal, mechanical, and electrical. Specific numerical calculation procedures were developed to simulate the response of the sensors. The approach accurately modeled the pressure response and thermal behavior based on fundamental physics and material properties. However, membrane parallelism defects that result in loss of sensitivity were not considered in the study.

In 2002, Dibi developed a new approach to model a structure with four piezoresistance type P connected in the Wheatstone bridge. The simulation included studying the impact of parallelism defect on both sides of the membrane and the effect of actual dimensions of gauges as a function of their positions on the membrane.

In 2006, Pramanik created a mathematical model to use the variable overlay approach to solve the heat transfer equation for a variable-speed circular structure. To calculate the growth in resistance temperature, she used PSpice to develop a thermal model. The equivalent thermal circuit's temperature rise can be calculated from this model as a function of the voltage at the thermal capacity's terminals by using a relationship between the parameters of the equivalent thermal circuit and those of the membrane design [2].

In 2009, Olszacki's work aimed to improve the analytical models used for simulating piezoresistive or capacitive pressure sensors. The author used finite element simulations to validate and optimize these models, as well as manufactured and characterized test cells to compare their behavior to recognized analytical models. The study revealed significant inaccuracies in the models typically used to characterize the thermal drift of piezoresistance. A theoretical method for analyzing and correcting thermal drifts in silicon piezoresistive pressure sensors was presented by Ras Lain. His strategy for calculating temperature expansion coefficients was based on mobility models. In doing so, he was able to combine the influence of these coefficients and the piezoresistivity coefficient on silicon's resistive behavior. He suggested two methods for adjusting the offset voltage's thermal drift.

In 2014, Zhou has the author proposed an intelligent temperature compensation system to reduce the impact of temperature on sensor accuracy in gas oil lines. The system involves designing an efficient conditioning circuit for data acquisition and signal processing, followed by practical pressure measurement tests to verify system performance. The temperature compensation range is -40 to 85°C.

In 2016, Honeywell Sensing and Control released pressure sensors for ceramic silicon (HSC) installations with excellent accuracy from Tru Stability. These sensors offer great precision, dependability, and stability over a broad temperature range.

In 2017, A high-performance barometric pressure sensor with exceptionally low power consumption, the BMP380, was unveiled by Bosch Sensortec. It was created for usage in battery-powered wearable’s and other gadgets.

In 2019, The D6T-1A-01, a non-contact MEMS thermal sensor from Omron Electronic Components, is designed to detect temperature changes in a variety of applications, such as security systems, HVAC systems, and industrial automation.

In 2020, The InvenSense ICP-20100 MEMS capacitive barometric pressure sensor was made available by TDK Corporation. It was perfect for use in portable devices since it had a tiny form factor, great precision, and required little power.

I.3.MEMS (Micro-Electro-Mechanical Systems):

Microsystems are small-scale (their characteristic dimensions range from 1 µm to 1 mm), devices that offer a cost-effective alternative to conventional precision electrical measurement technologies. They are characterized by their small size, low energy consumption, high reliability, and integration into electronic components. These microsystems often include mechanical actuators, sensors, and other devices that use physical phenomena involving micro-machined structures. They also feature integrated microelectronic circuits and are capable of exchanging information with the outside world or with other microsystems. Overall, microsystems are compact, multifunctional, and miniaturized devices that offer a wide range of potential applications [5].

In 1992, Analog Devices introduced a microsystem, a fully integrated silicon accelerometer measuring 10 mm2 for vehicle shock detection. It has a capacitive accelerometer sensor, signal processing, and an electrostatically driven actuator for selftesting. This exemplifies the trend toward more intelligent and autonomous technology. The ability to create analog and signal processing circuits as well as surface micro-machining is made possible by the interoperability of VLSI technology and sensor technology. An essential quality of microsystems is their interdisciplinary nature .

I.4.Description of pressure sensors:

Sensors convert a physical quantity into an electrical signal using either variation in the physical properties of the sensitive element (passive sensors) or exploiting appropriate physical effects (active sensors). The electrical signal obtained represents an image of the physical quantity being measured. A pressure sensor consists of a sensitive cell and a conditioning circuit. The sensitive cell measures the pressure while the conditioning circuit processes the data [13].

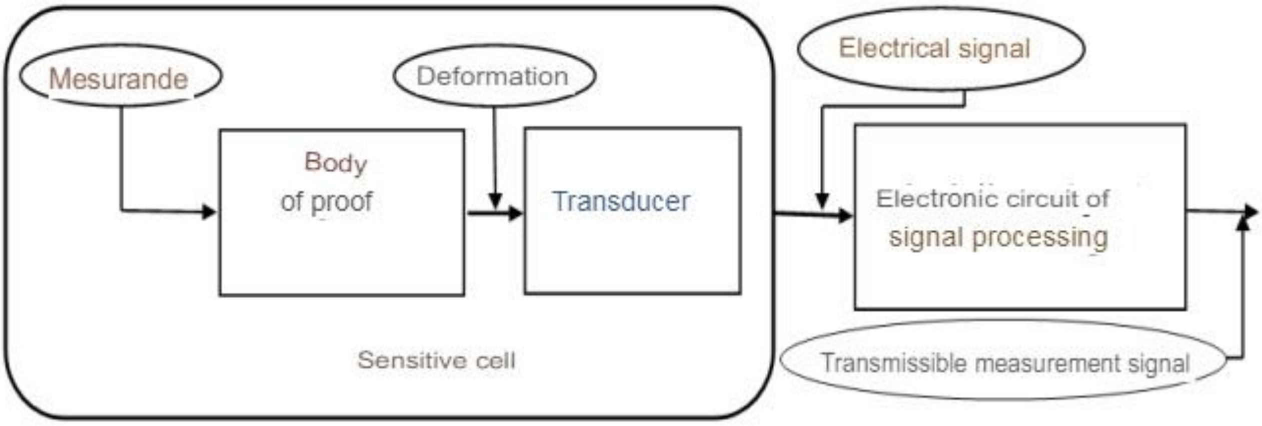

Figure I.1: Block diagram of a pressure sensor

The pressure sensor consists of two parts: The sensing part «sensitive cell» is a «Body of proof» and a «Transducer» and a part of information processing: The electronic circuit of signal processing.

- Body of proof: The physical quantity to be measured, such as pressure, causes deformation in a mechanical element known as the sensitive cell. The deformation is then transformed into an electrical signal, which can be processed and measured. Commonly used mechanical elements for pressure sensors include plates, beams, and diaphragms. and nowadays, pressure sensors often use a silicon membrane as the sensitive cell due to its superior mechanical and physical properties. The deformation of the membrane in response to pressure changes is then converted into an electrical signal.

- Transducer: The sensing element of a pressure sensor is directly in contact with the body to be measured and is used to convert the body’s reaction into an electrical signal. To measure the pressure.

  The sensitive element of a pressure sensor can produce an electrical signal in the form of voltage, current, or charge. This signal is generated by converting the reaction of the sensor to the measured pressure into an electrical output.
- Electronic circuit of signal processing: The electronic circuit associated with a pressure sensor is responsible for converting, compensating, or adjusting the sensor's output signal into a standard electrical signal such as current, voltage, or charge. This circuit is typically integrated with the sensor and is responsible for generating an electrical signal that accurately reflects the deformation of the sensor's proof body and thus the pressure being measured. The advancement in microelectronics has enabled the incorporation of new technologies into the electronic processing circuit of pressure sensors. Additionally, digital techniques have facilitated the addition of various functionalities to the sensors, including error correction, self-diagnosis, networking with external systems, and local processing and calculations.

I.5.The main characteristics of the sensors:

The accuracy and limitations of a sensor are determined by its specific metrological characteristics, which are influenced not only by the measured quantity but also by other factors that can disrupt the sensing element. Some common metrological characteristics of sensors include:

- The range of measurement: The measurement range refers to the range of values that the sensor can accurately measure for the input quantity or measurement.
- Sensitivity: This refers to the ability of the sensor to detect and respond to changes in pressure. It is usually expressed as the ratio of the change in the output signal to the change in input pressure.

- Accuracy: This is the degree of conformity of the output signal to the true value of the input pressure. It is affected by various factors such as temperature, humidity, and noise.
- Linearity: This is the degree to which the output signal varies linearly with changes in input pressure.
- Range: This is the minimum and maximum values of input pressure that can be measured by the sensor.
- Hysteresis: This is the difference in output signal for the same input pressure when the pressure is increasing or decreasing. It is caused by the elastic deformation of the sensing element.
- Stability: This is the ability of the sensor to maintain its metrological characteristics over time and under different operating conditions.

I.6.Advantages and disadvantages of pressure sensors:

I.6.1.Piezoresistive:

a) Advantages:

Piezoresistive pressure sensors are a popular choice in various industries and biomedical applications .here are some advantages and disadvantages of Piezoresistive pressure sensors:

- High sensitivity: Piezoresistive sensors have high sensitivity to pressure variations, making them ideal for measuring small changes in pressure.
- High linearity: The response of Piezoresistive sensors is linear over a wide range of pressures, making them accurate and reliable for use in various applications.
- Low power consumption: Piezoresistive sensors typically require low power to operate, making them suitable for battery-powered devices.
- Easy signal processing: The electrical output signal of Piezoresistive sensors is directly proportional to the applied pressure, making signal processing relatively simple and straightforward.

b) Disadvantages:

Piezoresistive sensors are not without their limitations, which include the following disadvantages.

- Temperature sensitivity: Piezoresistive sensors can be sensitive to changes in temperature, which can affect their accuracy and require additional calibration procedures.
- Overload limitations: The high sensitivity of Piezoresistive sensors also means that they can be easily damaged by pressure overloads beyond their range.
- Long-term stability: Piezoresistive sensors may experience drift or degradation in their sensitivity over time, which can affect their long-term stability and require periodic recalibration.
- Limited pressure range: Piezoresistive sensors may have limitations in their pressure range, depending on their design and construction.

I.6.2.Capacitive:

a) Advantages:

- High accuracy and resolution
- Low power consumption
- Insensitivity to magnetic fields
- Good stability over time
- Wide temperature range.

b) Disadvantages:

- Susceptibility to mechanical shock and vibration
- Limited pressure range compared to other types of sensors
- Requires a high excitation voltage
- Sensitivity to environmental factors such as humidity and dust
- Difficult to compensate for temperature effects.

I.7.Pressure sensors:

I.7.1.Definition:

Is to convert a physical quantity into an electrical signal that can be processed and utilized by a measuring system or device. There are many different types of sensors, each designed to measure specific physical quantities such as pressure, temperature, light, motion, and more. The mathematical equations used to represent the output of a sensor are based on the physical laws that govern the behavior of the measured quantity and may need to be corrected or supplemented by experimental data to ensure accurate measurement. Sensors are used in a wide variety of applications, from simple household devices like thermostats and motion detectors to complex scientific instruments and industrial control systems.

A sensor transforms a physical quantity into an electrical input signal. The output signal or sensor response is the exploitable quantity. The response must be independent of foreign magnitudes or taken into account in the equation governing the response. The sensor is the first link in any measurement chain and data acquisition system. Variations in the characteristics of a sensitive element or physical effects are used to provide electrical information.

I.7.2.Piezoresistive pressure sensors:

Piezoresistive pressure sensors are transducers that use the piezoresistive effect, which is the alteration in electrical resistance of specific materials (often silicon), to translate mechanical pressure into an electrical signal. Piezoresistive pressure sensors are a well-liked option for accurate pressure measurements because of their high sensitivity, high linearity, and simplicity of signal processing.

Silicon is the ideal material for electrical signal generation from mechanical deformation. The study of this crucial feature has been the focus of numerous theoretical and experimental studies with the goal of developing extremely effective piezoresistive pressure sensors. Due to their simplicity, these sensors in the field of research offer a lot of potential for usage in numerous applications.

Since temperature fluctuations are known to affect silicon piezoresistive pressure sensors, the accuracy of the sensor's output may be impacted by an offset voltage. The goal of Aljancic's study was to comprehend how temperature and thermal drift affect the offset voltage of these sensors. He carried out tests to gauge the level of heat stress on the sensor's membrane and put forth a plan for reversing the temperature drift in the offset voltage. This method was empirically confirmed by the study, which also emphasizes the significance of taking temperature effects into consideration when utilizing piezoresistive pressure sensors in a variety of settings.

Modeling the mechanical behavior of the membrane is crucial for enhancing the sensor's pressure responsiveness. The Lagrange equation of order 4, which governs the deflection of a plate that is perfectly immersed at the edges, has a number of solutions that can be determined for minor and large deformations.

I.7.3.Capacitive pressure sensors:

Capacitive pressure sensors are pressure sensors working according to the principle of capacity. They are composed of the mobile septum and fixed electrodes. If the pressure changes, the diaphragm moves and changes the distance between the two electrodes, thereby changing the capacity. A capacitive pressure sensor was created by Ben Moussa using the MOS transistor manufacturing method. To ascertain how a silicon membrane would react if it were put under pressure, he employed the Galerkin semi-analytical approach. The linearity and sensitivity of the variable capacitor's behavior were examined.

The thermal behavior of capacitive pressure sensors with a fixed aluminum frame and a silicon membrane on a Pyrex substrate was studied by Blasquez. The temperature coefficient of the capacity was calculated in the study as a function of the membrane, fixed plate, and cavity dimensions using 3D numerical modeling and sensor readings. The findings demonstrated that the temperature coefficient was influenced by the thermomechanical deformations of the internal cavity and was sensitive to the width of the welded connection and the fixed panel thickness. It was discovered that the temperature coefficient was modest and comparable to that of the stationary plate.

Using printed circuit boards (PCBs), Souilah developed a low-cost and simple-to-integrate approach for producing capacitive pressure sensors. The sensors' geometry can be changed to suit certain applications. An experimentally studied prototype that was made has a sensitivity of 20.13 fF/mbar. Thermomechanical modeling and simulations are needed for further research since thermal drifts in the sensors are complicated. The success of a project depends heavily on the optimization of sensor performance, which can be aided by robust simulation software. To better understand how different factors affect sensor sensitivity, these models offer detailed physical and mechanical information on the sensor structure. It is therefore required to conduct more research on the thermomechanical behavior of these sensors.

a) Mechanical behavior:

1. The mechanical operation of a silicon piezoresistive pressure sensor was investigated.
2. The COMSOL Multiphysics environment was used to simulate using the finite element approach.
3. The maximum deflection and typical stresses at the media of the membrane edges were calculated using the model.
4. Based on the pressure exerted to the sensor, analysis was performed.
5. Piezoresistive gauge configurations' impact was also investigated.
6. Understanding how gauge configurations affect the sensor output voltage is made easier with the aid of simulation.
7. The work sheds light on how well piezoresistive pressure sensors function.
8. The mechanical analysis of sensors is a good application for the finite element approach.
9. Through simulations, the sensor design can be further optimized.

b) Thermal behavior:

In the same investigation, we examined how the ambient temperature affected the maximum deflection at the center and the maximum stresses at the middle of the membrane edges. In addition, we investigated the impact of temperature and doping on the output voltage while taking into account the whole sensor construction (membrane, gauges, and substrate). We looked into this phenomena produced by internal heating in the piezoresistance after the results revealed that the temperature elevation significantly altered the sensor's response. A DC voltage of 3–10 V powers the Wheatstone bridge commonly employed in piezoresistive pressure sensors, which leads to thermal drift and Joule heating. We created a numerical model utilizing the data from this sensor type to assess the impact of this effect.

The authors conducted research to study the effect of applied tension on heat distribution along the piezoresistance. They calculated temperature evolution for different geometric parameters and operating times to optimize the sensor's performance. The results showed that optimizing geometric parameters reduces internal heating and low polarisation voltage must be applied to reduce Joule heating. The authors also developed a COMSOL Multiphysics model to study the thermal behavior of capacitive pressure sensors, taking into account the structure, thermal effects due to temperature, and geometric parameters.

In this study, we used COMSOL Multiphysics to analyze the overall sensor structure (membrane + substrate). The capacitive response and pressure sensitivity of the sensor were determined as well as its resting temperature and temperature sensitivity. We also studied the effects of the geometric parameters of the membrane on the sensor response. This work focused on the impact of temperature on the output characteristics of pressure sensors. This research allowed us to predict the effect of temperature on the sensor’s performance and optimize its geometric parameters to minimize this effect.

I.8. Conclusion:

The first part of the chapter provides an overview of piezoresistive and capacitive pressure sensors, including their main features, performance, design, and manufacturing methods. The second part presents a literature review on sensors, microsensors, and MEMS, covering the majority of the work done in this field. To enhance their performance and optimize their properties, we will introduce models that predict their mechanical and thermal behavior.

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ChapterII :

Piezoresistive pressure sensors

II.1.Introduction:

A pressure sensor that makes use of the piezoresistive effect to gauge pressure changes is known as a piezoresistive pressure sensor. The term "piezoresistive effect" describes how a material's electrical resistance changes in response to mechanical stress or strain. A membrane or diaphragm constructed of a piezoresistive material, such as silicon or polysilicon, is used in a piezoresistive pressure sensor to transform the applied pressure into a change in electrical resistance [1].

Since they have been in use for more than 25 years, silicon pressure sensors with membranes have improved in accuracy thanks to microtechnology. Now, manufacturing is achievable on 1 mm diaphragms. To provide great precision for high pressures, a fixed barrier with solid core sections is employed instead of the typical square or round diaphragm .

High precision pressure sensor use is necessary in a number of fields. They serve as the initial points of contact for any measurement, control, or perception systems. The study of piezoresistive pressure sensors is the main topic of this chapter. As a result, we give a brief overview of these devices' functionality at the outset of this study.

II.1.1.Description:

The sensing cell and the signal processing component make up the piezoresistive pressure sensor. A test body and a piezoresistive transducer make up the sensing component, which transforms the test body's deformation into an electrical signal. A silicon wafer with a micro-machined membrane embedded in it is welded to a hard substrate to form the test body of the sensor under consideration. The test body deforms and becomes stressed in the presence of external pressure. Stress gauges, often of the P-type, are dispersed across the membrane's surface and linked by a Wheatstone bridge, allowing these stresses to be translated into variations in resistance [2].

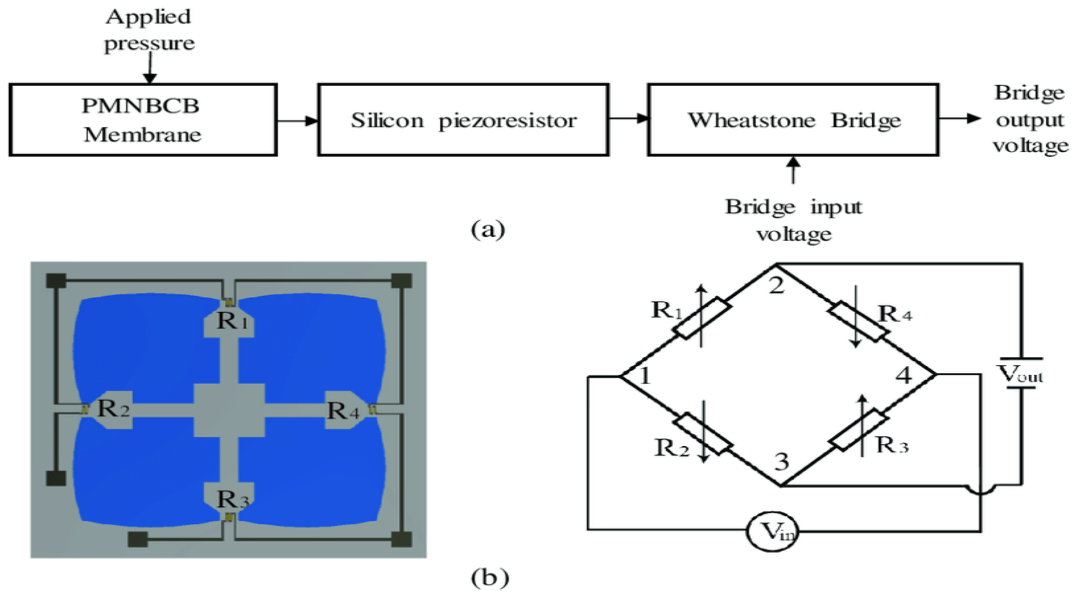


Figure II.1: Synoptic drawings of a piezoresistive pressure sensor [3]

II.1.2.Operating Principle:

It is feasible to predict the mechanical and electrical behavior of these sensors with respect to various factors, including the shape of the membrane, the properties of the materials employed, and the working circumstances, using numerical modeling and simulation. By lowering the number of iterations required to produce an optimal sensor, this strategy saves development costs and delays. Numerical simulation additionally offers a thorough comprehension of the underlying physical phenomena, which may result in further developments in sensor design. In this chapter, we examine piezoresistive pressure sensors with the goal of enhancing their functionality and optimizing their design [4].

The framework that is being offered calls for the creation of a mechanical model of the membrane, for which we will give a summary of the mechanical and physical characteristics of silicon, the material utilized in the construction of the device. Additionally, we conduct a theoretical analysis of how temperature and doping affect the piezoresistivity coefficient. In order to facilitate virtual prototyping and lower development costs, these initiatives seek to improve the device's performance and optimize its design.

Next, we start by simulating the membrane's mechanical behavior. We were able to validate our model by contrasting the acquired results with those found in the literature. We were able to establish the ideal placement for the gauges that served as the sensors thanks to this analysis. By first measuring the diaphragm deflection and normal stress as a function of rest pressure and temperature, we then evaluate the overall structure of the sensor (diaphragm and gauge). We then investigate how doping, temperature, and piezoresistive gauge components affect the output voltage of the piezoresistive pressure sensor.

II.2.Mechanical and physical properties of silicon:

Silicone is a perfect material for the microelectronics sector due to its numerous significant mechanical and physical qualities. Since silicon is a semiconductor and can have its electrical connection adjusted by introducing various impurities, it is a perfect material for the semiconductor industry, which is utilized in the manufacturing of integrated electrical circuits. Silicone is an excellent material for creating mechanical parts that are subject to mechanical loading because of its high mechanical qualities, which include being solid, long-lasting, robust, and able to endure pressure and tension. since of its unique physical characteristics, silicone is a great material for heat-exposed parts since it can withstand high temperatures and is unaffected by thermal changes. Silicone is available in large quantities and cheap, making it an ideal material for use in large industries and industrial production in general .

When cutting silicone, it is essentially cut into a level (100) aligned in two directions bases <100 > and < 110 >. This is done because silicone shows excellent electrical properties in these directions, and it gives better performance in electronic processes when used in these directions. Silicone is typically used in integrated circuit-making technology in the form of a thin, flat disc called abundant. The main advantages that make silicon the most popular material in microsystem manufacturing are:

1. Silicone has a relatively low density (2.33 g/cm3) when compared to other materials.
2. On the Moss scale of hardness, silicone has a high hardness rating of 6-7.
3. Durability Silicone is utilized in the production of electronic chips because it can flex well without breaking.

4. Thermal Conductivity of Silicone is used to make semiconducting semiconductors and coolers and is known for its ability to carry heat well.
5. Electrical resistance of Silicone has a high electrical resistance, which makes it a crucial component of electronic devices and the semi-conductive industries.
6. Silicone has a good diffusion in other materials, which facilitates the production of electronic chips in specific technical ways.
7. Melting point of Silicone melting point is roughly 1414 ° C, making it a heat-resistant material.

a) Strain tensor:

Materials can withstand stress in different forms, such as bending, tension, compression, torsion, shear, and more, which can lead to different types of deformation. Deformation of a material can occur when mechanical forces are applied to it and are determined by a change in the shape of the material when subjected to those forces.

The relationship between stress and strain in the material, which can be represented by a second-order symmetric tensor, a mathematical term used to describe the relationship between variables in mathematical equations, is known as the stress-strain relationship and is used to determine the state of deformation at any time.

In general, The mechanical characteristics of the material, including its hardness, elasticity, tensile strength, shear and compression strengths, and other characteristics, might influence deformation. Therefore, the kind of stress placed on the material and its mechanical characteristics determine the kind of deformation that takes place.

For instance, deformation in the shape of the material can happen when a tensile force is applied to it, pulling the material in various directions, when a compressive force is applied, pushing the material from all sides, and when a bending force is applied, deformation happens in the shape of the material along the axis that it is bent.

In general, figuring out a material's mechanical properties and understanding how it responds to stress can assist pinpoint how deformation happens.

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \qquad (II.1)$$

b) Stress tensor:

Stress is a force that acts on a certain body, causing it to change in size or shape. By dividing the force acting on the surface by the surface's overall area, stress is computed. Pascal's units or N/m2 are commonly used in the international system to measure stress. Stress from these pressures can be evaluated using appropriate engineering and physics equations.

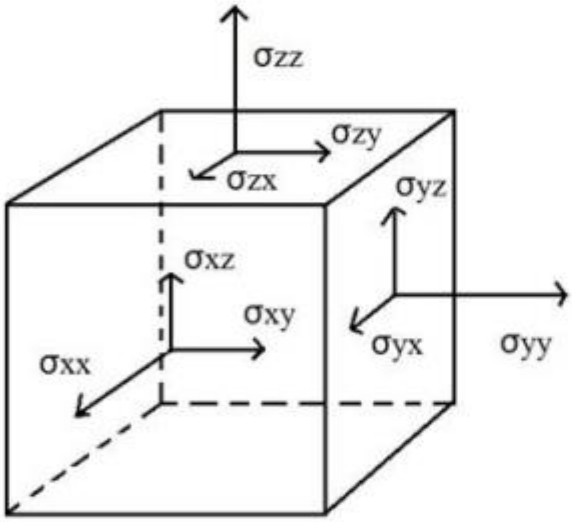


Figure II.2: Mechanical stress tensor components

To represent stress at a specific point in a material, the stress tensor is used. Stress in a small volume of material is expressed in terms of a stress tensor that has nine independent elements, which are defined at the base of the crystallographic axes.The form of tension at the particular point can be expressed using the tension matrix, and this matrix can be represented using the following formula:

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \qquad \text{(II.2)}$$

When in a state of equilibrium, the stress tensor σ xy exhibits symmetry such that σ xy = σ yx and is comprised of six components that are considered to be independent.
The stress tensor, however, must be symmetric because of the conservation of angular momentum. The components xy and yx are therefore equivalent. In addition, the stress

tensor has just six independent components as opposed to the nine that one may anticipate. This is due to the symmetry of the stress tensor and the relationship between the diagonal components, xx, yy, and zz, as shown by the equations of equilibrium [5].

II.2.1.Piezoresistivity phenomenon:

Piezoresistivity is a phenomenon whereby mechanical stress causes a material's electrical resistance to vary. Depending on the type of material and the stress direction, the change in resistivity can either be positive or negative.

In 1856, British physicist William Thompson, known as "Lord Kelvin" ,first noticed the impact of electrical pressure change sensing. It was later discovered that the electrical resistance of the metal strip is influenced by its strength because raising the pressure acting on the conductor causes the electrical current flowing through it to decrease.

Piezoresistive pressure sensors, which contain a metal substance that is affected by pressure changes and results in a change in its electrical resistance, have been created using this feature. To identify the pressure influencing the devices, the change in resistance can be measured.

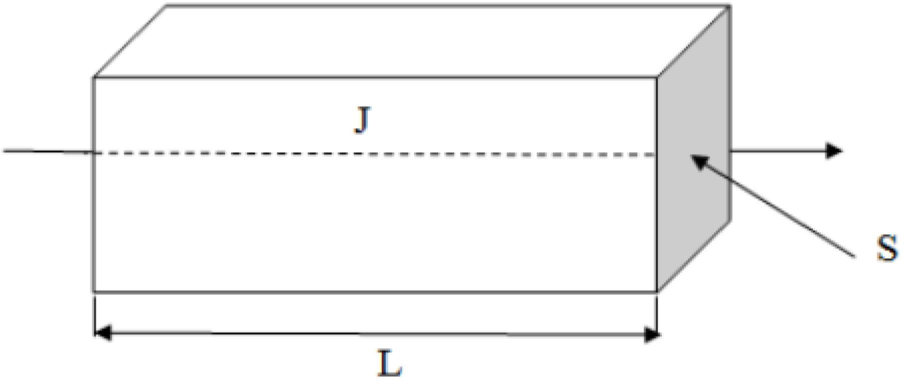


Figure II.3: R resistance of block shape

It is feasible to determine the electrical resistance R of the jauge by applying an electric current J to it along its length L and using the equation II.3.

$$R = \rho\frac{L}{S} \quad (II.3)$$

Where L is the resistance's length in m, S is its section expressed in m2, and ρ is its resistance.

Electrical resistance value can be controlled by one of the following two methods:

Dimension Change: The resistance of the material increases as the width or fish drops and decreases as the length increases, and the opposite is true as the width or fish decreases as the length increases.

Change the material's special resistance: By adjusting the material's exposure to different temperatures, pressures, or tensions, the particular resistance of the material can be altered. Additionally, alternative materials with different electrical resistance, such as silicon, graphene, or various metals, can be employed to create the sensitive device.

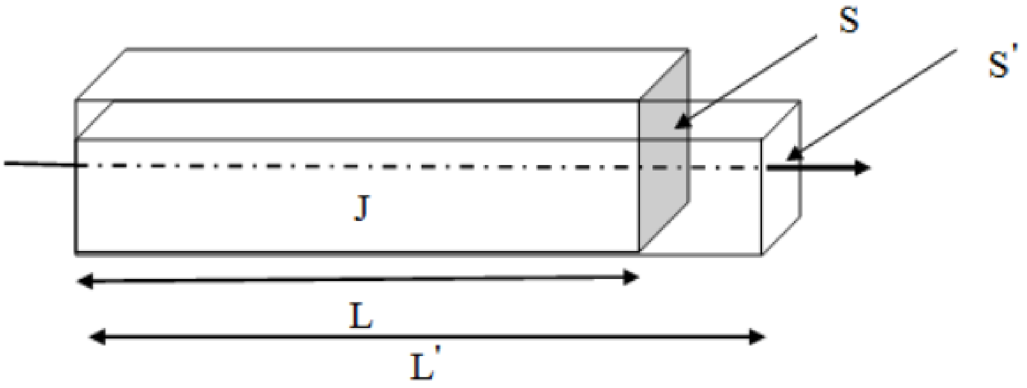


Figure II.4: The strength of a material bar under stress

Under the application of stress or strain, a material's resistance might change, which can result in a change in the material's lateral dimension.

$$R' = \rho\frac{L'}{S'} \qquad (II.4)$$

The variation in resistance can be expressed generally as follows:

$$\frac{\Delta R}{R} = \frac{\Delta\rho}{\rho} + \frac{\Delta L}{L} + \frac{\Delta S}{S} \qquad (II.5)$$

Where $\frac{\Delta\rho}{\rho}$ is the relative change in resistivity, $\frac{\Delta L}{L}$ is the longitudinal strain, $\frac{\Delta S}{S}$ is the transverse strain.

In metallic scales (strain gauges), resistance changes mainly as the severity of deformation in their geometry changes, and this is known as the phenomenon of piezoresistivity. So the terms $\frac{\Delta L}{L}$ and $\frac{\Delta S}{S}$ will be successful in determining the overall resistance change, the resistance of the dividing gauge varies mostly as a result of its resistance adjustment. For the semiconductor-based scale, the first term, alienation (Eq. II. 5), which is largely dominant, describes the change in resistance caused by the application of restrictions.

The relation II.6 can be rewritten in the following form:

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L}(1 + 2v) \qquad \text{(II.6)}$$

Most materials, whether conducting or semiconducting, exhibit this dual effect of stress on the electrical and mechanical properties of the rod. Depending on the kind and atomic structure of the semiconductor, the relative changes in the three terms of II.6 reflect this effect in practice and are of variable significance.

As we learned in the previous section of this chapter, each element of the cubic crystal will be subject to normal and shear stresses when considering a restricted bar (**Figure II.4**) (**Figure II.2**). It was claimed that resistivity and geometric dimensions are the two factors that can alter the value of electrical resistance. Contrary to metal gauges, silicon has a resistance that varies by 99% due to changes in its resistivity, which are then followed by changes in its shape. Applying a restriction alters the number and mobility of the carriers in a piezoresistive material like silicon, which in turn alters the resistivity .

The piezoresistive effect refers to the variation in resistivity of a material in response to applied mechanical stresses. In the case of silicon, this effect is very significant and anisotropic, which means that resistivity varies differently depending on the direction of the applied stresses.

Equation II.7 is used to express it:

$$\rho = \rho_0 + \rho_0 \pi \sigma \qquad \text{(II.7)}$$

Where ρ_0 is the resting resistivity of a homogeneous material.

The relationship between the electric field E and the current flow J in a semiconductor material is as follows:

$$E = (\rho + \Delta\rho)\ J \qquad \text{(II.8)}$$

II.3.Sensor modeling and simulation:

II.3.1.Membrane Modeling:

Membranes can be modeled in different ways depending on the specific context and goals of the modeling. Common approaches to membrane modeling include:

- Linear elasticity model: The membrane is viewed as a linear elastic material in this concept. The behavior of membranes is described using equations from the mechanics of continuous media, such as the traction equation or the equilibrium equation. The stiffness and strength of the material are two key elements in this model.
- Plate theory model: The model is based on thin plate theory. He viewed membranes as two-dimensional plates and used plate bending equations to describe their behavior. This model is useful when the bending deformation of the membrane is large compared to other deformation modes.
- Hull model: This model incorporates three-dimensional effects while being similar to the plate theory model. It is appropriate for membranes with irreversible transverse deformations.
- Viscoelastic behavior model: The model takes into account the viscoelastic behavior of the membrane, meaning its response depends on time and applied stress. The model is suitable for membranes that exhibit significant relaxation or creep behavior.

It is important to remember that each model has its own presumptions and restrictions, and the choice of model will depend on the precise properties of the membrane and the goals of the modeling. The equations of the selected model can be solved numerically using techniques like the finite element method or the finite difference method to produce quantitative predictions about membrane behavior.

II.3.2.COMSOL Simulation:

IT has evolved significantly in recent years, which has resulted in many powerful programs being used in various fields such as engineering, science, and technology. These advanced programs I mentioned include: COMSOL offers great flexibility in creating complex models and studying multiphysics phenomena. It can be used to model all material aspects relevant to sensor design, from electrical and magnetic engineering to thermal, mechanical and fluidic. You can perform parametric studies to improve sensor performance, e.g. B. To analyze the effect of changing the materials used, technology dimensions, or operating conditions on the sensor's electrical and mechanical performance criteria. You can closely simulate the behavior of the sensor and get near to its actual structure by using numerical computations and convergence techniques. Additionally, COMSOL can be used to evaluate findings and draw significant conclusions about the effectiveness and optimization of sensors .

We will compute the greatest stress at the midpoint of the membrane edge and the maximum deflection at the membrane's center to verify this model. We will also look into how deflection and normal stress change depending on the surrounding temperature. In order to understand how doping, temperature, and various piezoresistive gauge configurations scattered throughout the membrane affected the sensor's output voltage, we also carried out research including these variables. It's vital to remember that we looked at how these characteristics affected the sensor's response.

The design of the numerical model involves partial differential equations that govern the behavior of our system, known as the COMSOL PDE model. These equations describe the physical phenomena and interactions occurring within the system. The COMSOL PDE model allows us to simulate and analyze the behavior of our system under different conditions, providing valuable insights into its performance. By solving these equations numerically, we can obtain a detailed understanding of the system's behavior and make informed design decisions.

The Lagrange equation of order 4 in Cartesian coordinates, expressed in compact form, governs the mechanical behavior of a square membrane as follows:

$$-\nabla\sigma = F \qquad (II.9)$$

F stands for the volumetric (or masstric) forces, where is the constraint tensor. Equation II.9 below provides the constraint-deformation relation.

$$\sigma = \sigma_0 + C_{:} \cdot (\varepsilon - \varepsilon_{th}) \qquad (\text{II.10})$$

The elasticity tensor $C_{:}$ is represented as follows:

$$C_{:} = \frac{E}{(1+v)(1-2v)} \begin{bmatrix} 1-v & v & v & 0 & 0 & 0 \\ v & 1-v & v & 0 & 0 & 0 \\ v & v & 1-v & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2v}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2v}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2v}{2} \end{bmatrix} \qquad (\text{II.11})$$

Initial stresses are represented by 0, initial deformations by 1, and thermal deformations by 2.

The following format summarizes the steps taken to simulate a model in COMSOL's multi-physics environment:

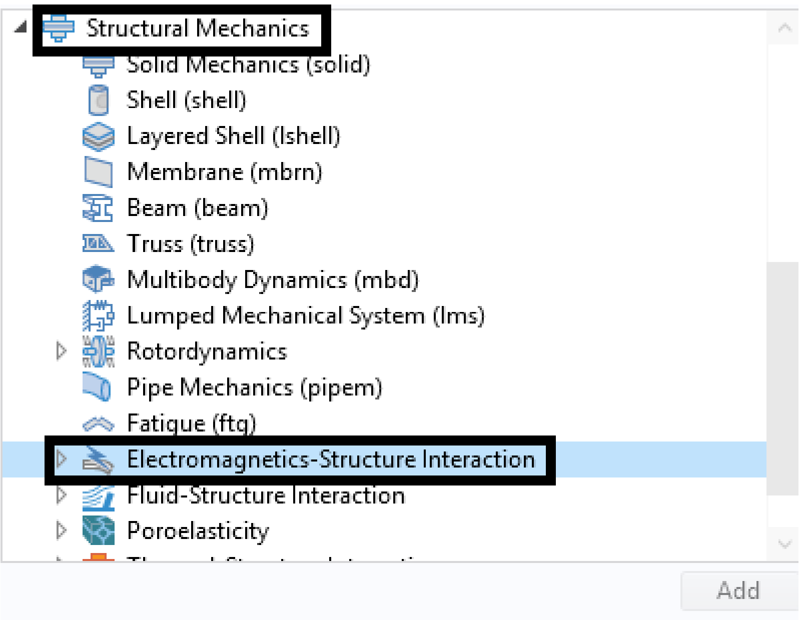
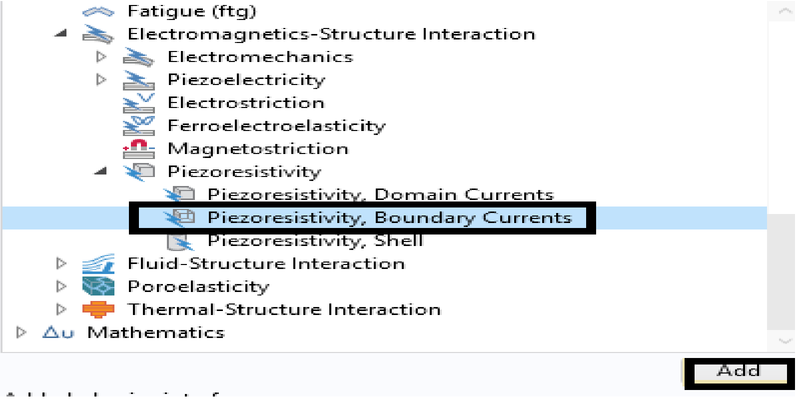
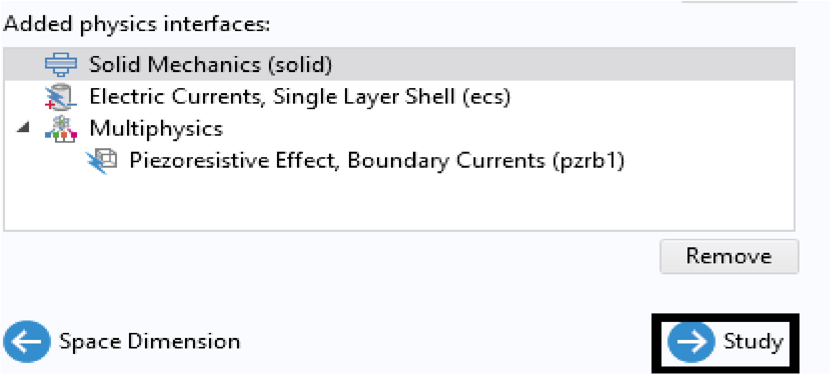


Figure II.5: Choice structural mechanics and electromagnetic-structure interaction



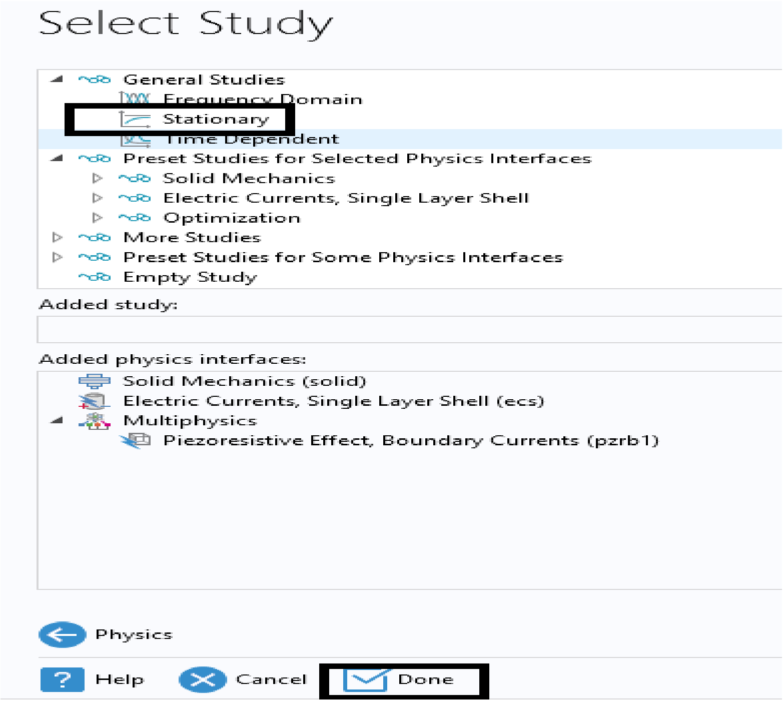
Fatigue (ftg)
Electromagnetics-Structure Interaction
Electromechanics
Piezoelectricity
Electrostriction
Ferroelectroelasticity
Magnetostriction
Piezoresistivity
Piezoresistivity, Domain Currents
Piezoresistivity, Boundary Currents
Piezoresistivity, Shell
Fluid-Structure Interaction
Poroelasticity
Thermal-Structure Interaction
Mathematics

Figure II.6: Choice Piezoresistivity, Boundary currents and click Add



Added physics interfaces:
Solid Mechanics (solid)
Electric Currents, Single Layer Shell (ecs)
Multiphysics
Piezoresistive Effect, Boundary Currents (pzrb1)

Figure II.7: Click Study



Select Study

General Studies
Frequency Domain
Stationary
Time Dependent
Preset Studies for Selected Physics Interfaces
Solid Mechanics
Electric Currents, Single Layer Shell
Optimization
More Studies
Preset Studies for Some Physics Interfaces
Empty Study

Added study:

Added physics interfaces:
Solid Mechanics (solid)
Electric Currents, Single Layer Shell (ecs)
Multiphysics
Piezoresistive Effect, Boundary Currents (pzrb1)

Figure II.8: Click Stationary and click Done

Simulation Steps in COMSOL Multiphysics Environment:

Engineering creation: Utilizing COMSOL design tools create divisive pressure sensor engineering. It could be necessary to design a 3D geometry that contains the composite sensor pieces.

Material Definition: Give details on the mechanical, thermal, and electrical resistance characteristics of the materials used to make the sensor.

Determining border conditions: Identify the sensor's suitable border circumstances. This can include factors like electrical conductivity, outside pressure, feeding, and discharging conditions.

Definition of equations: For the divisive pressure sensor, use the suitable physical equations. Equations for stress, deformation, electrical conductivity, and any additional equations relating to these are included.

Run simulation: Run the simulation and monitor the progress and numbers. You might have to modify the simulation's settings and add any necessary enhancements as you go.

Results analysis: Utilize the COMSOL analysis tools to examine the outcomes and comprehend M's behavior.

Geometry:

Figure (II.8) depicts the two-dimensional geometry of the piezoresistive pressure sensor for the model created using COMSOL Multiphysics. A square-shaped membrane with a four resistors are positioned correctly, with R1 and R3 being longitudinal and R2 and R4 being transverse, as part of a Wheatstone bridge connection.

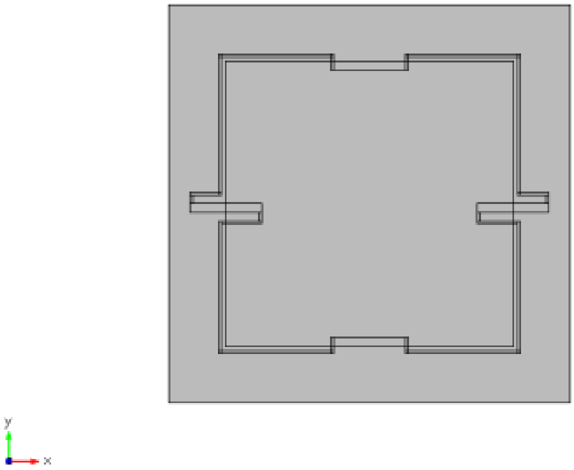


Figure II.8: Top view of geometry under COMSOL.

II.3.2.1.Membrane simulation:

a) Study in relation to pressure:

Figures II.9, II.10, display the outcomes of the simulation of the established model. These images depict the curves for normal stresses σ_{xx} (σ_{yy}) and shear σ_{xy} in the plane (xoy) for P=100 kPa, as well as variations in membrane deflection w(x, y).

According to known theory, Figure II.9 demonstrates that the membrane deflection is greatest in the middle. According to Figure II.10, normal stresses σ_{xx} (σ_{yy})are maximally positive at the membrane edge media and maximally negative at the middle of the membrane as a function of the pressure applied. Therefore, it is obvious that one of the ideal sites for the gauges in the construction of piezoresistive pressure sensors is in the middle of the membrane's edges for higher sensitivity to pressure.

Note that the normal stresses on ox and oy (σ_{xx} and σ_{yy}) are identical, since the membrane is square.

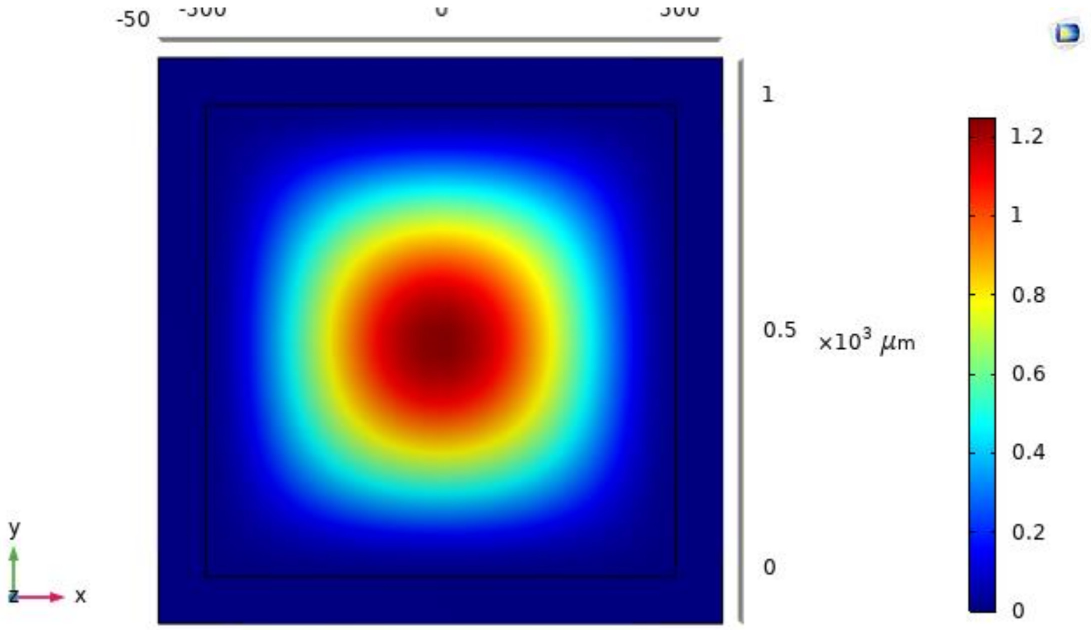


Figure II.9: Deflection w(x,y) for P=100 kPa

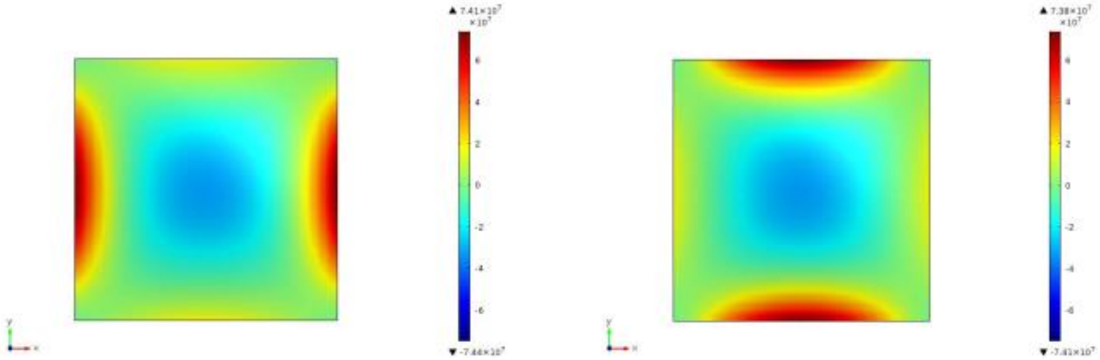


Figure II.10: Normal constraints σ_{xx} and σ_{yy} for P=100 kPa

A square-shaped membrane with dimensions of a = 1000 µm in length and d = 20 µm in thickness was taken into account in this simulation. Keep in mind that these criteria were chosen from the literature to support the concept. The Young, Coulomb G, and silicon Poisson module values employed in this simulation are provided by:

E= 0 .16892 GPa;

G= 0.05092 GPa;

v= 0.0642;

II.3.2.2.Sensor simulation:

The sensitivity to sensor pressure depends on the position of the different gauges on the test body. Based on the membrane study, it is recalled that we have determined that the normal stresses are maximum at the edges and middle of the membrane, allowing for several possible configurations as shown in figure II.11 [6].

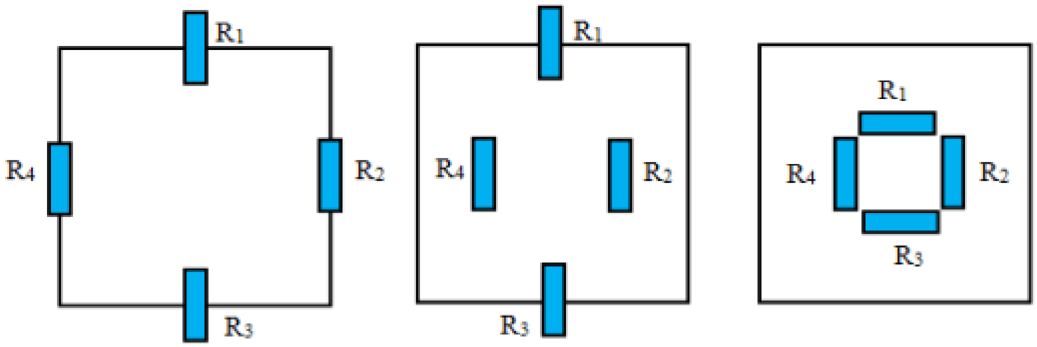


Figure II.11: Different gauge configurations on a membrane [6]

In our case, we used the configuration shown in Figure II.8, which is the most commonly used and has high pressure sensitivity. The application of uniform and constant pressure on the membrane, perfectly embedded at the edges, gives rise to a deflection w(x, y) (figure II.12), which is subsequently translated into stresses (figure II.13), which are in turn converted into resistance variation by the piezoresistive effect.

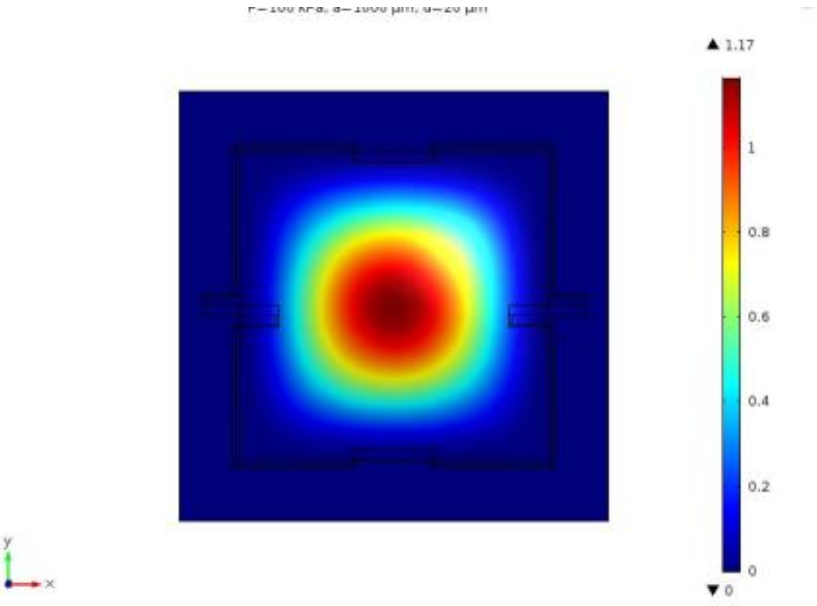


Figure II.12: W(x, y) membrane of the entire sensor structure.

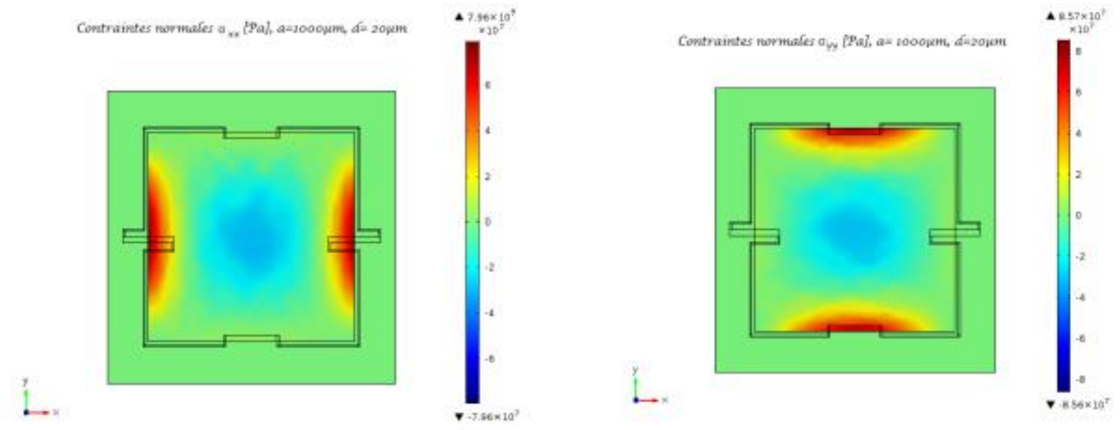


Figure II.13: 2D representation of normal constraints σ_{xx} and σ_{xx} respectively

II.4.Conclusion:

The key theoretical underpinnings required to comprehend the piezoresistive pressure sensor, its operating principle, and its key features have been covered in this chapter. In order to compare and validate the model developed within the COMSOL Multiphysics environment, we provided a number of theoretical models for the resolution of the Lagrange equation.

We configured our digital model in a COMSOL environment after validating our model. This enables us to calculate how the membrane's deflection varies with pressure and temperature, as well as how normal stresses are produced. The influence of doping, temperature, and gauge arrangement on the sensor output voltage were then investigated for the sensor as a whole (membrane and gauges). This demonstrates that a thermal stress exists.

We will focus the third chapter on the investigation of thermal drift brought on by the Joule effect in square membrane piezoresistive pressure sensors because the output response is highly impacted by temperature.

References:

[1] S. Vittoz, "Modélisation et caractérisation de capteurs mécaniques intégrés a based'heterostructures A1GaN/GaN pour les environnements hostiles," Thèse de Doctorat,Université de Toulouse, 2013.

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[5] J.J. Vlassak, W.D. Nix, "A new bulge test technique for the determination of Young's modulus and Poisson's ratio of thin films," Journal of Materials Research, vol. 7, pp. 3242-3249, 1992.

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Chapter III: Impact of the Drifts Caused by the Bias voltage on the in Pressure Sensors

III.1.Introduction:

The most common example involving heat transfer is a system consisting of two bodies in contact at different temperatures. The hottest body gives some of its energy, in the form of heat, to the coldest body. So there’s a heat transfer between these two bodies. This heat transfer can be perceived positively or negatively, depending on the objective. The problems of energy transmission, and in particular of heat, have been of decisive importance in the study and operation of apparatus such as steam generators, furnaces, heat exchangers, evaporators, condensers, etc., but also piezoresistive pressure sensors.

Many physical, electrical, or geometric parameters can cause non-ideal piezoresistive pressure sensors. One can cite the temperature generated by the Joule effect when supplying these devices with a voltage source as a physical and electrical parameter. These parameters significantly affect the measurement accuracy by minimizing the pressure sensitivity of the sensor. This chapter focuses on the influence of these parameters on the output characteristics of the sensor when applying a power supply voltage to optimize its performance.

In order to do this, we devote a part to the generalities of heat transfer and its three modes of transfer. A second part is then reserved for interpretations of the results obtained concerning the thermal drift caused by heating by the Joule effect in piezoresistive pressure sensors.

III.1.2.Thermal Transfer:

Heat transfer is defined as thermal energy in motion due to a temperature difference in the same medium or between two media. We encounter these phenomena of heat transfer in everyday life (central heating at home using water exchangers, processes used in the industrial environment, etc.). The study of these transfers is carried out by the intervention of three types of simultaneous or isolated mechanisms: conduction, convection, and radiation.

a) Conduction:

It is defined as the mode of heat transmission caused by the difference in temperature between two regions of a solid, liquid, or gaseous medium or between two media in physical contact.

At the microscopic level, it represents the process of heat propagation by direct contact between the particles of a body or between bodies having two energy levels and thus different temperatures due to the movement of these elementary particles . In gases, heat transfer by conduction is the result of molecular diffusion, but in liquids and dielectric solids, it is done by elastic waves. In the case where the solid is conductive, the heat transfer by conduction is mainly due to the diffusion of free electrons from the warmer to the colder zones; this is the case of heating by the Joule effect . Conduction heat transfer can be used in various technological applications and is governed by the following equation [1]:

$$\Delta\left(K_{(x,y,z,t)} * T(x,y,z,t)\right) + q = \rho\, C_p \frac{\partial T(x,y,z,t)}{\partial t} \qquad \text{(III.1)}$$

Where $k_{(x,y,z,t)}$,are the thermal conductivities of materials expressed in W.m^{-1}.K^{-1}, for silicon k = 150, q is the volumetric heating flow rate by effect Joule expressed in W.m^{-3}, ρ is the density in kg.m^{-3}, for silicon ρ=2320, Cp is the heat capacity of the material expressed in $J.K^{-1}.kg^{-1}$, for silicon C_p= 712, T (x, y, z, t) is the temperature field in the solid expressed in °C, and t is the time in seconds (s). To simplify the calculations, we consider that the thermal conductivity is independent of the temperature that we note as k. The heat equation is then written as follows:

$$\Delta T(x,y,z,t) + \frac{q}{k} = \frac{1}{\alpha}.\frac{\partial T(x,y,z,t)}{\partial t} \qquad \text{(III.2)}$$

Where α $(=k / \rho C_p)$ is the thermal diffusivity in $m^2.s^{-1}$, for silicon α = 0.9*10^{-4}.

b) Convection:

The phenomenon of convection is the mode of transmission that involves the displacement of elementary particles of the fluid, liquid, or gas between zones having different temperatures; this mixture generates exchanges of quantity of movement and thermal energy .

This phenomenon refers to the heat transfer that occurs between a solid surface and a no stationary fluid when they are at different temperatures. On the surface of a solid, the convective heat flux is proportional to the temperature difference between the surface of the solid and the temperature of the fluid and is given by the following Newton's law [2]:

$$\phi_{conv} = h(T_s - T_f) \tag{III.3}$$

Where ϕ_{conv} is the convective flux expressed in W/m² and h=2.219Wm^{-2}K^{-1} is the silicon convection coefficient.

c) Radiation:

The phenomenon of thermal radiation constitutes a particular mode of thermal transfer in which the energy carrier is no longer composed of particles. This mode of heat transfer does not require material support; the radiation energy is transported by electromagnetic waves [1]. This type of heat transfer is produced by the emission and absorption of these waves and is characterized by its efficiency in vacuum.

For heat transfer by radiation from a surface to a temperature Ts, the total emittance E is governed by the law of Stefan-Boltzmann [1]:

$$E = \varepsilon.\sigma_s.h.T_s^4 \tag{III.4}$$

Where the total emittance E is expressed in W.m^{-1}, $\sigma_s$is the Stefan-Boltzmann constant (σ_s=5,67.10^{-8} W/m².K^4) and ε is the emissivity coefficient of the area ($0 \le \varepsilon \le 1$).

III.2. Modeling of the Joule effect in pressure sensors:

The silicon-based piezoresistive pressure sensors have found wide application in various fields, such as automotive, aerospace, and biomedical instruments. They have the advantages of high *Sp* sensitivity, excellent electrical response linearity, good technological compatibility, small size, low power, mass production, etc. However, they often suffer from the influence of temperature on their response. It is therefore necessary to carry out a study of their thermal behavior in order to determine the parameters that cause these drifts in their output characteristics.

Zahidand al. [3] studied thermal drift in piezoresistivemicrocantilevers caused by Joule heating. They presented an approach that focuses on analytical and numerical techniques to characterize heat transfer by conduction in these devices. Subsequently, these same authors developed another precise model that takes conduction and convection into account to predict the thermal behavior of these piezoresistivemicrocantilevers.

Since the origin of the thermal drifts in the pressure sensors is due not only to the thermal constraints of the technological manufacturing process but also to the heat transfer mechanisms between the different layers of the sensor.

We will devote this chapter to the study of the temperature rise generated by internal heating in piezoresistive pressure sensors when polarizing the bridge with a voltage source. These sensors, powered by a voltage of 3 to 10 V, involve thermal drifts that greatly alter their response.

In order to determine how the temperature affects these kinds of sensors, we have established the expression of the temperature field variation generated by the internal heating of its piezoresistance for the different geometric parameters of the slide as well as for different times of its operation. The evolution of the piezoresistance factor, the piezoresistivity coefficient, and the pressure sensitivity as a function of time and voltage of the V_0 supply for the different geometric parameters are also analyzed. This study allows us to improve the reliability of the sensor and optimize its response.

Other modes of heat transfer are neglected in this work, and only conduction is considered the only mode of heat energy transfer, as shown in Figure III.1. Where d is the thickness of the membrane in µm, a is the side of a square-shaped membrane given in µm.

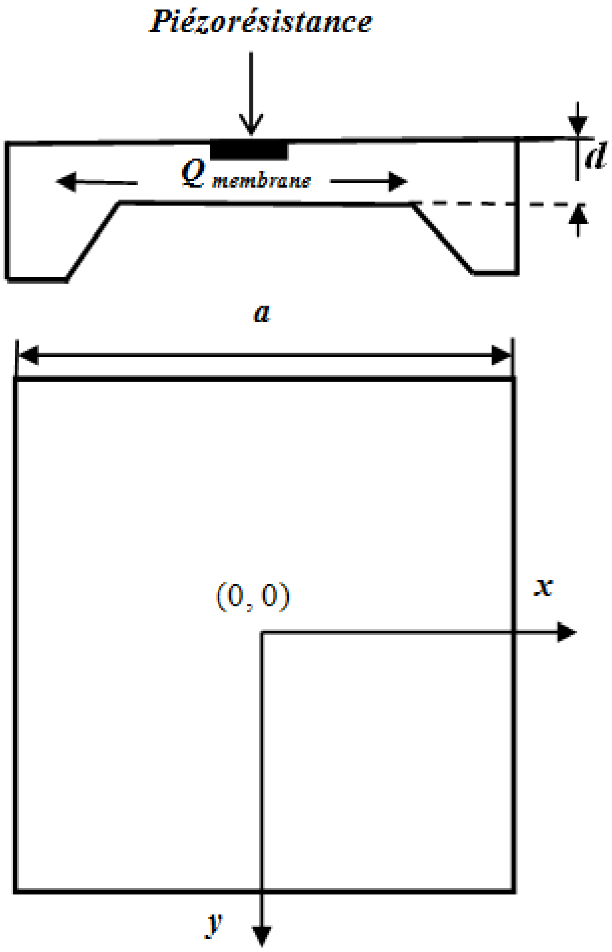

Figure III.1: Square membrane piezoresistive pressure sensor structure

In this chapter, a *2D* solution of the heat conduction equation is developed into cartesian coordinates for the variable speed by the finite differences method (*FDM*). We will couple the temperature variation in the resistance generated by the Joule effect with that in the membrane by conduction. For this, we solve a coupled system consisting of two differential equations. While neglecting the temperature variation along the perpendicular direction, the heat transfer equation for the resistance is given as follows:

$$\Delta T_1(x,y,t)+\frac{q_1}{k_1}=\frac{1}{\alpha_1}.\frac{\partial T_1(x,y,t)}{\partial t} \qquad \text{(III.5)}$$

While the heat transfers equation in the membrane is written:

$$\Delta T_2(x,y,t)+\frac{q_2}{k_2}=\frac{1}{\alpha_2}.\frac{\partial T_2(x,y,t)}{\partial t} \qquad \text{(III.6)}$$

III.2.1.Finite Differences Method:

The finite differences method is a technique for finding approximate solutions to partial differential equations by means of Taylor development. It consists of solving a system of relations linking the values of unknown functions at certain points sufficiently close to each other, called nodes.

The first step of this method consists of subdividing the structure into rectangular cells, whose rows and columns are parallel to the *ox* and *oy*, axes, respectively. The position of a point in the structure is indicated by the indices '*i*' and '*j*' (*i* is the position of the point on the *ox* axis, and *j* is the position of the point on the *oy* axis).

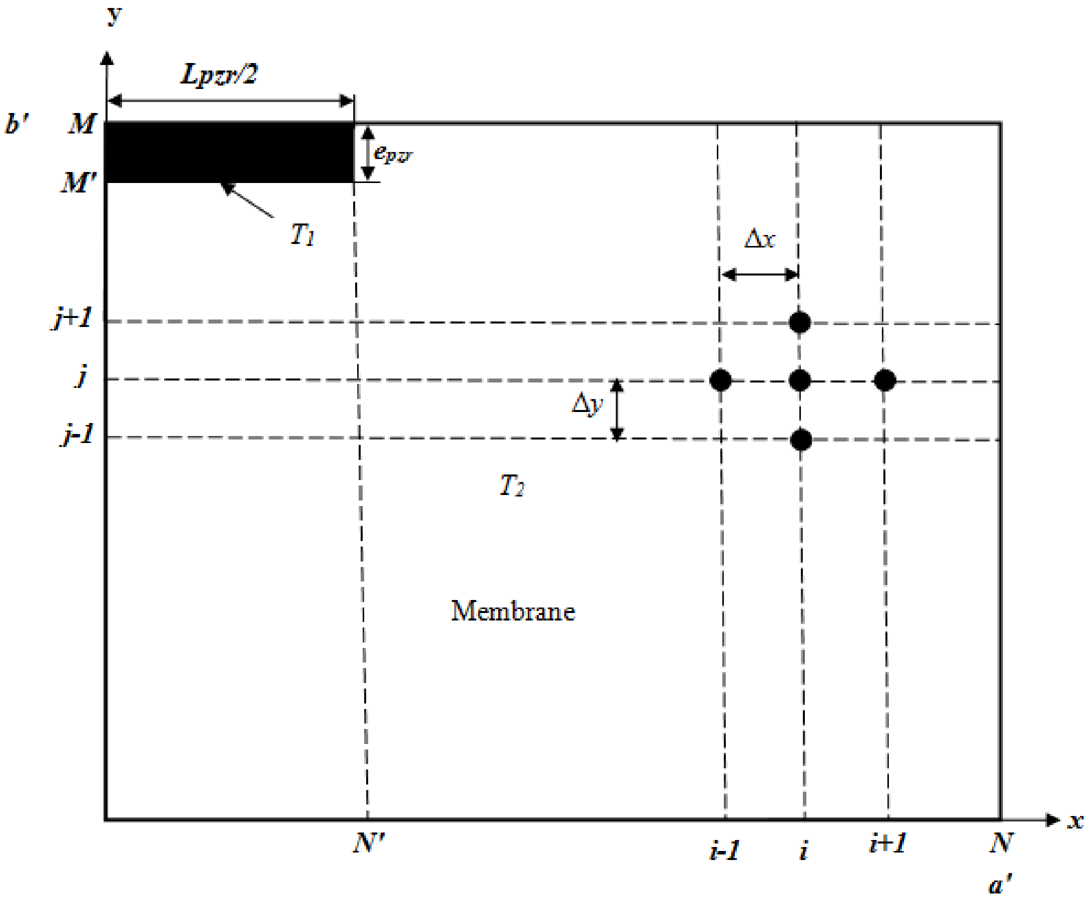

Figure III.2: Mesh structure illustrates the mesh of the resistance and membrane by this method.

Where L_{pzr} and e_{pzr} respectively represent the length of the piezoresistance and its width, T_1 is the temperature in the piezoresistance caused by electric heating, while T_2 describes the temperature in the membrane due to conduction.

The conditions at the applicable limits in strength and membrane (**Figure III.2**) are:

By symmetry, we have:

$$\begin{cases} x = 0 \rightarrow \dfrac{\partial T_1}{\partial x} = \dfrac{\partial T_2}{\partial x} = 0 \\ y = 0 \rightarrow \dfrac{\partial T_2}{\partial y} = 0 \end{cases} \tag{III.7}$$

In addition:

$$x=a', -k_2 \frac{\partial T_2}{\partial x} = h\left(T_2(a', y) - T_0\right) \tag{III.8}$$

$$y=b' \text{ and } 0<x<L_{pzr}/2 \; -k_1 \frac{\partial T_1}{\partial y} = h\left(T_1(x, b') - T_0\right) \tag{III.9}$$

$$y=b' \text{ and } L_{pzr}/2<x<a' \; -k_2 \frac{\partial T_2}{\partial y} = h\left(T_2(x, b') - T_0\right) \tag{III.10}$$

Conduction according to the axis *ox*:

$$y=b'-e_{pzr} \text{and} 0<x<L_{pzr}/2 \; -k_1 \frac{\partial T_1}{\partial y} = -k_2 \frac{\partial T_2}{\partial y} \tag{III.11}$$

Conduction along the *oy* axis:

$$x=L_{pzr}/2 \text{ and } b'-e_{pzr} < y < b' \; -k_1 \frac{\partial T_1}{\partial x} = -k_2 \frac{\partial T_2}{\partial x} \tag{III.12}$$

The conditions for continuity of temperatures along the *ox* axis are:

$$0<x<L_{pzr}/2 \qquad T_1(x, b'-e_{pzr}) = T_2(x, b'-e_{pzr}) \tag{III.13}$$

As for the continuity of temperatures according to the *oy* axis, it is necessary:

$b'-e_{pzr}<y<b'T_1(L_{pzr}/2,y)=T_2(L_{pzr}/2,y)$ (III.14)

The energy generation rate q_1 in resistance is given by:

$$q_1 = \frac{V_0^2}{Rda^2} \qquad \text{(III.15)}$$

Where R is the spread resistance in Ω given by the following expression [11, 12]:

$$R = \rho_e \frac{L_{pzr}}{A_{pzr}} \qquad \text{(III.16)}$$

With ρ_e denoting the electrical resistivity and A_{pzr} the resistance section.

The initial condition throughout the structure is:

$$T_1(x,y,t)\big|_{t=0} = T_2(x,y,t)\big|_{t=0} T_0 \qquad \text{(III.17)}$$

III.2.2.Discretization of the Equation System (MDF):

The second step of this method is the discretization step, which consists of transferring differential equations to partial derivatives in an algebraic equation system that describes the same physical phenomena at the different nodes of the domain using the implicit scheme because it does not require a stability condition on space and time steps .

In our case, the heat equation is discredized in space and time. To do this, you have to generate a spatial division into two zones; the time is also divided into a discrete period, called the time step.

The space steps are Δx and Δy, and the time step is Δt, so we have $a'=(N-1)\Delta x$, $b'=(M-1)\Delta y$ ett$_k$$=k\,\Delta t$.

If we pose $T(x_i, y_j, t_k)= T(i, j, k)$ with $i=1,...N$ and $j=1,...M$,then the discretization by the finite difference is given as follows:

$$\frac{T_n(i+1,j,k)-2T_n(i,j,k)+T_n(i-1,j,k)}{\Delta x^2}+\frac{T_n(i,j+1,k)-2T_n(i,j,k)+T_n(i-1,j,k)}{\Delta y^2}+\frac{q_n}{k_n}=\frac{1}{\alpha_n}\frac{T_n(i,j,k)-T_n(i,j,k-1)}{\Delta t} \qquad \text{(III.18)}$$

Where n=1 for resistance and n=2 for membrane.

Ask :

$$A_1=\frac{\alpha_1\Delta t}{\Delta x^2},\; B_1=\frac{\alpha_1\Delta t}{\Delta y^2},\; C_1=\frac{q_1\alpha_1\Delta t}{k_1}$$
$$A_2=\frac{\alpha_2\Delta t}{\Delta x^2},\; B_2=\frac{\alpha_2\Delta t}{\Delta y^2},\; C_2=\frac{q_2\alpha_2\Delta t}{k_2} \qquad \text{(III.19)}$$

If we replace the expressions of A_n, B_n and C_n from equation III.19 in III.18, we obtain:

$$B_nT(i,j-1)+A_nT(i-1,j)-\left(2A_n+2B_n+\frac{1}{\alpha_n\Delta t}\right)T(i,j)+A_nT(i+1,j)+B_nT(i,j+1)=-\frac{1}{\alpha_n\Delta t}T(i,j,k-1)-C_n \qquad \text{(III.20)}$$

The inner nodes are:

i=1,....,N'-1 and j=M'+1,.... M-1 for resistance et *i=2,....,N-1 et j=2,.... M'-1*membrane.

When we apply the boundary and initial conditions throughout the structure and perform all the calculations, we thus obtain a system of linear equations in the matrix form [A] [T] = [B] to be solved numerically by the Thomas algorithm using Matlab.

III.3.Parameters of influence on temperature generation:

In this section, we will study the increase in temperature due to internal heating when applying a bias voltage for different sensor operating times as well as its various geometric parameters. The silicon material properties used in this work are shown in Table III.1.

settings	values
Density, ρ (kg / m^3)	2320
Coefficient of heat transfer, h (Wm^{-2}K^{-1})	2.219
Electrical resistivity, ρ_e (Ω.m)	10^{-3}
Thermal conductivity,K (Wm^{-1}K^{-1})	150
Specific coefficient of heat, C (J / kgK)	712
thermal diffusivity,α (m^2 / s)	$0.9*10^{-4}$

Table III.1: Silicon properties

III.3.1. Numerical study using Mobility Model:

The self-heating issue arising from electrical potential often gives rise to temperature drifts, a significant drawback of piezoresistive pressure sensors. Nevertheless, these sensors are still the most broadly used in several fields [4]. To optimize the output characteristics, it is crucial to investigate the impact of bias voltage on these sensors. Thus, extensive research studies have been conducted to minimize this effect. An examination of the effect that the supply voltage and geometric attributes of piezoresistors had on the thermal characteristics of microcantilever sensors was introduced by Zahid and colleagues [5]. Their approach encompassed the use of analytical and numerical models to determine the internal heating within these sensors. Consequently, we also decided to apply a numerical model to investigate the thermal drift in piezoresistive pressure sensors, thereby understanding the influence it had on the pressure sensitivity of these sensors. Several models of hole mobility developed by Boukabache et al. are utilized to study the effects of doping on the temperature-environment behavior of a silicon resistor. By doing so, the reliability of sensors can be estimated, along with an improvement in sensitivity due to the obtained results. Piezoresistance in pressure sensors is investigated in this study through theoretical and numerical means. The mobility model used is specific to p-type silicon and is paired with the finite difference methodology relating to internal heating. The main focus is on tailoring the effect of bias voltage on piezoresistivity. Arora mobility and electric heater finite difference models are combined for the research presented. The evolution of mobility with the operating times of sensors has been computed for several doping levels as well as for the temperature produced by self-heating. Further, the study seeks to explore the parameters influencing mobility to optimize the response of the device.

Many physical, electrical, or geometric parameters make piezoresistive pressure sensors less than ideal. As a physical and electrical parameter, it can be named the temperature generated by self-heating when these devices are operated with a voltage source. These parameters have a significant impact on measurement accuracy by minimizing the pressure sensitivity of the sensor. This study highlights the impact of these parameters on the mobility when a supply voltage is applied, thereby affecting the output characteristics of the sensor. Mobility is a fundamental physical parameter that determines the functionality of electronic components such as sensors. In this study, we are interested in the effect of self-heating on the mobility of pressure sensors.

In this case, we neglect the other modes of heat transfer, and we only consider conduction as the only mode of thermal energy transfer as shown in **Figure III.1**.

Mobility in a piezoresistor is greatly affected by temperature, specifically that induced by the internal heating effect when the bias voltage is applied to the sensor. This effect is governed by the following equation (III.1):

Otherwise, By offsetting equation (III.16) in equation (III.15), we obtain equation (III.21), which represents the rate of energy production through self-heating:

$$q = \frac{A_{pzr}}{Lpzr.d.S_m}\frac{V_0^2}{\rho_\varepsilon} \tag{III.21}$$

Where V_0 is the electrical potential, d is the membrane thickness, S_m is the area of the square-shaped diaphragm, *Lpzr* is the length of the piezoresistance, *Apzr* is the cross-sectional area, and ρ_e is the electrical resistivity.

After the discretization of this equation by the latter, we obtained a system of linear equations that is solved by the Thomas method using Matlab. As part of the reliability studies of these sensors, we focused on the thermal drift in mobility during their operating time. So, we use the Arora mobility model formula given by [6]:

$$\mu(T) = \mu_{mn} \frac{\mu_{0n}}{1+\left(\frac{N_A}{N_{cn}}\right)^{\theta}} \tag{III.22}$$

Where μ_{mn} is minimal of mobility, μ_{0n} the difference between the maximum and minimum value of mobility, N_{cn} the concentration reference and θ is an exponential factor. The final mobility expression is:

$$\mu(T) = 88\left(\frac{T}{300}\right)^{-0.57}\left(\frac{1250\left(\frac{T}{300}\right)^{-2.33}}{1+\left(\frac{N_A}{1.26\times10^{17}\left(\frac{T}{300}\right)^{2.4}}\right)^{0.88\left(\frac{T}{300}\right)^{-0.146}}}\right) \tag{III.23}$$

Results and Discussion:

As we have pointed out already, in general, piezoresistive sensors have an important shortcoming in the form of thermal drift, particularly those due to the bias voltage of the device. So, the temperature rise produced by self-heating in a piezoresistor strongly affects the performance of such sensors. This paper aims to put emphasis on the study of the geometrical and physical influences on mobility. This involves the numerical resolution of the heat transfer equation in a variable regime and in cartesian coordinates. Its solution can be written as follows:

$$T(t) = T_m(1-e^{-t/\tau}) + T_0 \tag{III.24}$$

Where T_m and τ are the constant and the thermal time constant, respectively. It should be noted that the validation of the results of a numerical model for self-heating can be found in our recent work. Afterwards, the mobility variations with the physical, electrical, and geometrical parameters are obtained by coupling the temperature expression (III.24) with Arora's mobility formula (III.23).

1. Effect of temperature rise and operating time on mobility:

In this section, we will establish the evolution of mobility according to the operating time of the sensor for various concentrations and the temperature created by the internal heating. As we can see in **Figure III.3** and **Figure III.4**, after operation of the device for a period of up to 180 min and under a voltage of 5 V, the mobility is a decreasing function with time and with doping level, as well as with temperature. Mobility is improved by a short operating time on the one hand and a low doping concentration on the other.

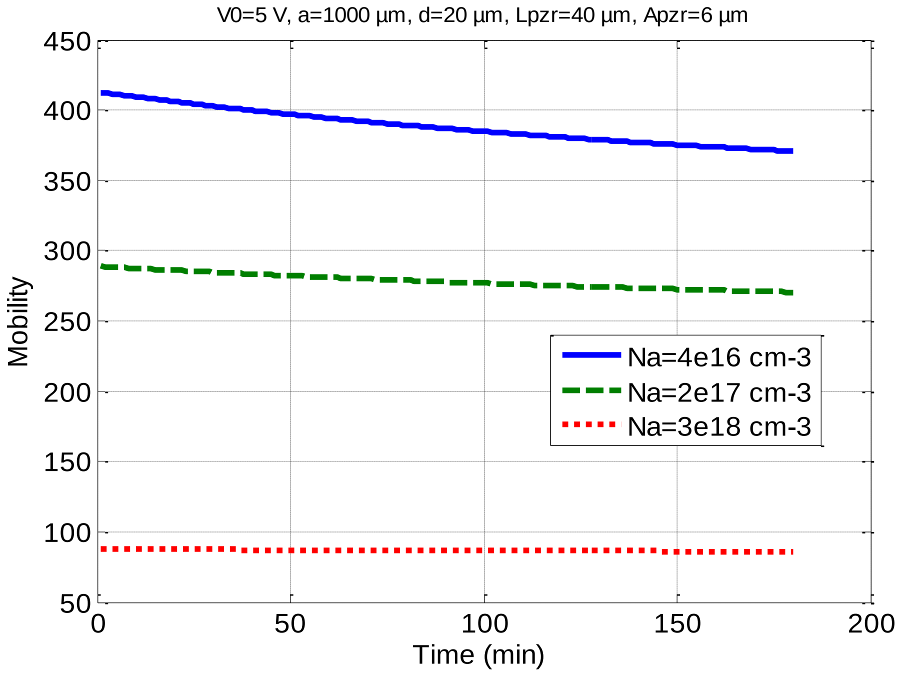

Figure III.3: Variation of mobility in operating time for several doping levels

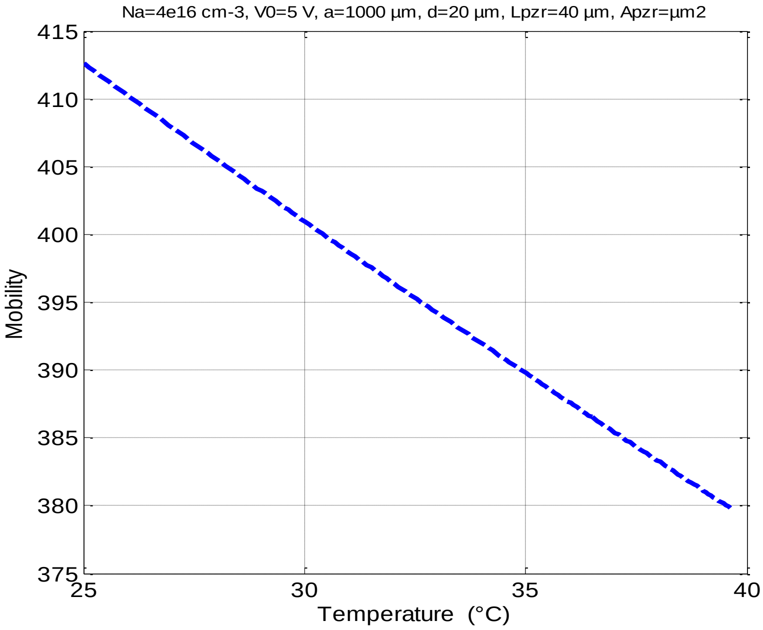

Figure III.4: Variation of mobility with temperature provoked by self heating

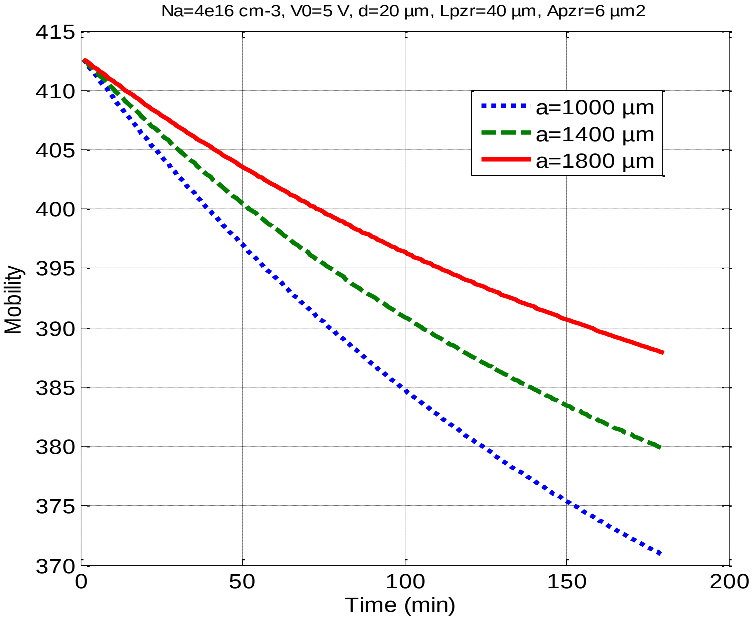

Figure III.5: Variation of mobility as function of time for various diaphragm side lengths

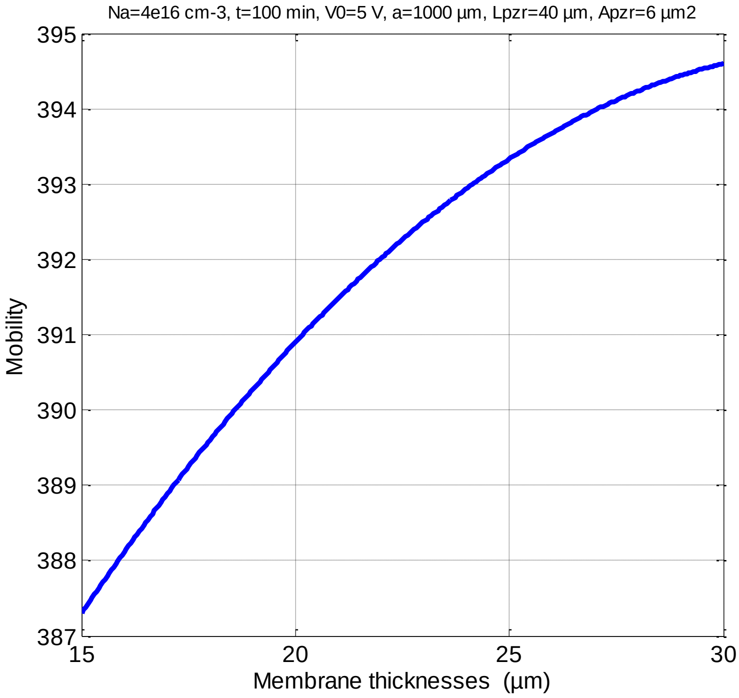

Figure III.6: Mobility variation with membrane thicknesses

2. Effect of geometric parameters of the membrane on mobility:

To highlight the effect of the geometric parameters of the structure, such as the thickness and side length of the membrane, on mobility, we have plotted their evolutions in Figure III.5 and Figure III.6. For a bias voltage of 5 V, there is a decrease in mobility as a function of the operating time of the device, as shown in the following figure (Figure III.5). On the contrary, it increases with the width of the membrane and its thickness. However, these two parameters are themselves constrained by other technological factors in manufacturing. These factors include device sizing, manufacturing accuracy, and reproducibility. In addition, the large size of the device leads to a reduction in pressure sensitivity.

3. Effect of applied voltage in mobility:

The knowledge of mobility evolution when the electric tension is applied is used to quantify the output characteristic from the thermal drifting. Knowing that mobility depends on temperature, it is obvious that the four piezoresistors of the pressure sensor also depend on it. Therefore, it certainly depends on the electrical bias voltage.

Combining the numerical model of self heating with that of Arora, we find the mobility versus supply voltage. As we can notice in **Figure III.7**, the highest mobility corresponds to a low applied potential. As a result, for high mobility values, the applied voltage must be low.

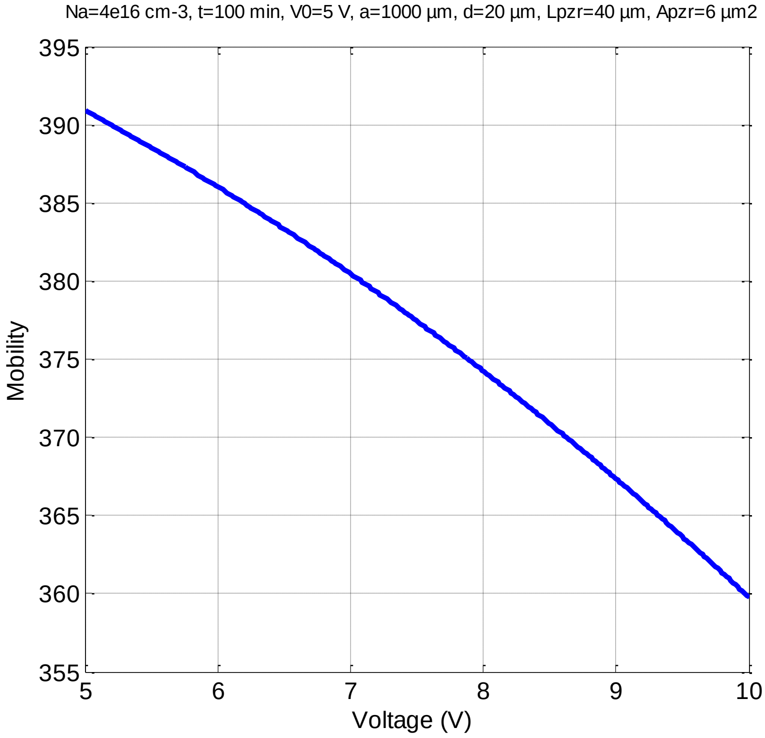

Figure III.7: Evolution of mobility with electric potential

III.4.Conclusions:

The findings of this study seek to enhance the performance of piezoresistive pressure sensors, specifically addressing thermal drifts resulting from electrical tension. By implementing a numerical model based on self-heating and Arara mobility, we have pinpointed the influence of various factors such as operating time, temperature increase, and doping levels. Ultimately, this research paper offers a valuable contribution to the field.

Against the temperature rise produced by an electric furnace, the mobility can be improved by utilizing the sensor for a brief period, and by marginally doping the piezoresistors. Additionally, we researched the effect that membrane's geometric parameters have on mobility. The research indicated that higher geometric parameters lead to increased mobility. Despite this, it causes a reduction in pressure sensitivity on one side and creates a larger-sized sensor on the other.

Moreover, since mobility decreases with an increase in temperature, a low bias voltage will be helpful for reducing the electrical heating effect on it.

To summarize, the drifting effects caused by self-heating in the output characteristics of sensors can be lessened by applying low supply potential. Thus, when the geometric parameters are great, It can be equally reduced if a high doping level is used. Note that these parameters are themselves restricted by the dimensions of the device, the sensitivity, and the reliability.

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General Conclusion

General Conclusion:

The modeling and thermomechanical simulation of silicon pressure sensors were the focus of this thesis.

We focused our attention on their contribution to improving the performance of pressure sensors by proposing models that predict the mechanical and thermal behavior of these devices and minimize the effect of temperature by optimizing their geometric parameters.

First, we set out to present a bibliographical study on the state of the art of piezoresistive pressure sensors.

Secondly, the study of the main theoretical foundations necessary for the understanding of their operating principle and their main characteristics has been established. Then, a model of finite elements under COMSOL Multiphysics consists of studying the mechanical behavior of the square-shaped piezoresistive pressure sensor. This model has made it possible to study the maximum stress exerted on the edges of the membrane and the maximum deflection in the center as a function of pressure.

In order to reduce the thermal drift of the self-heating, a modeling of the Joule effect heating in the square membrane piezoresistive pressure sensors was proposed. For this purpose, a numerical model for heat transfer resolution in Cartesian chords and variable speed using the finite differences method (FDM) has been established.

Abstract

Abstract:

The primary objective of the thesis is to investigate and model the thermo-mechanical behavior of pressure sensors with piezoresistive detection. The research begins with an extensive literature review to gain a comprehensive understanding of the current state of the art in these devices. This review covers the mechanical and physical properties of the materials employed in the fabrication of these sensors. the research focuses on studying the deflection at the center of the membrane and the stress experienced at its edges under different pressure and temperature conditions at rest.

In this study, our focus is on analyzing mobility, an essential electrical parameter of a piezoresistor, and its direct correlation with the piezoresistive effect in piezoresistive pressure sensors. We investigate the influence of temperature on mobility when an electrical potential is applied.

To accomplish this, we develop a theoretical and numerical approach based on the mobility of p-type silicon piezoresistors and a finite difference model (FDM) for self-healing. We analyze the evolution of mobility over time for various doping levels and temperature increases using a combined numerical model for mobility and self-healing. We also consider different geometric parameters of the sensor, such as the side length and thickness of the membrane, and examine mobility as a function of the bias voltage.

Extended operation of the sensor leads to a significant temperature-induced impact on mobility, resulting in output response drift. Our research enables prediction of temperature behavior, facilitates device optimization, and recommends reducing applied voltage to mitigate self-heating effects in piezoresistive pressure sensors. This research improves the understanding of temperature effects in piezoresistive pressure sensors, enabling prediction and mitigation of self-heating. Optimizing device geometry and voltage sources minimizes the impact of temperature on sensor performance.

Résumé :

L’objectif principal de la thèse est d’étudier et de modéliser le comportement thermomécanique des capteurs de pression avec détection piézorésistive. La recherche commence par un examen approfondi de la littérature pour acquérir une compréhension globale de l’état actuel de la technique dans ces dispositifs. Cet examen porte sur les propriétés mécaniques et physiques des matériaux utilisés dans la fabrication de ces capteurs.la recherche se concentre sur l’étude de la déviation au centre de la membrane et de la contrainte ressentie sur ses bords dans différentes conditions de pression et de température au repos.

Dans cette étude, nous nous concentrons sur l’analyse de la mobilité, un paramètre électrique essentiel d’un piezoresistor, et sa corrélation directe avec l’effet piezoresistif dans les capteurs de pression piezoresistive. Nous étudions l’influence de la température sur la mobilité lorsqu’un potentiel électrique est appliqué.

Pour ce faire, nous développons une approche théorique et numérique basée sur la mobilité des piezoresistors de silicium de type p et un modèle de différence finie (FDM) pour l’auto-guérison. Nous analysons l’évolution de la mobilité dans le temps pour différents niveaux de dopage et les augmentations de température en utilisant un modèle numérique combiné pour la mobilité et l’auto-guérison. Nous considérons également différents paramètres géométriques du capteur, tels que la longueur latérale et l’épaisseur de la membrane, et examinons la mobilité en fonction de la tension de polarisation.

Le fonctionnement prolongé du capteur entraîne un impact important de la température sur la mobilité, ce qui entraîne une dérive de la réponse de sortie. Notre recherche permet de prédire le comportement de la température, facilite l’optimisation des appareils et recommande de réduire la tension appliquée pour atténuer les effets d’auto-échauffement dans les capteurs de pression piézorésistifs. Cette recherche améliore la compréhension des effets de la température dans les capteurs de pression piézorésistifs, permettant la prédiction et l’atténuation de l’auto-chauffage. L’optimisation de la géométrie des appareils et des sources de tension réduit l’impact de la température sur les performances des capteurs.

ملخص:

الهدف الأساسي للأطروحة هو فحص ونمذجة السلوك الميكانيكي الحراري لمستشعرات الضغط مع الكشف المقاوم للانقسام. يبدأ البحث بمراجعة شاملة للأدبيات للحصول على فهم شامل للحالة الحالية للفن في هذه الأجهزة. يغطي هذا الاستعراض الخصائص الميكانيكية والفيزيائية للمواد المستخدمة في تصنيع هذه المستشعرات .يركز البحث على دراسة الانحراف في مركز الغشاء والضغط الذي يعاني منه في حوافه تحت ظروف ضغط ودرجة حرارة مختلفة عند الاستعادة.

في هذه الدراسة، ينصب تركيزنا على تحليل التنقل، وهو معامل كهربائي أساسي لمقاوم الضغوط، وارتباطه المباشر بالتأثير المقاوم للانقسام في مستشعرات الضغط المقاومة للانقسام. نحن نحقق في تأثير درجة الحرارة على التنقل عند تطبيق جهد كهربائي.

لتحقيق ذلك، نطور نهجًا نظريًا وعدديًا يعتمد على حركة مقاومات السيليكون من النوع pونموذج الاختلاف المحدود (FDM) للشفاء الذاتي. نحلل تطور التنقل بمرور الوقت لمستويات المنشطات المختلفة وزيادة درجات الحرارة باستخدام نموذج عددي مشترك للتنقل والشفاء الذاتي. ننظر أيضًا في المعلمات الهندسية المختلفة للمستشعر، مثل الطول الجانبي وسمك الغشاء، وفحص الحركة كدالة على جهد التحيز.

يؤدي التشغيل الممتد لجهاز الاستشعار إلى تأثير كبير ناتج عن درجة الحرارة على التنقل، مما يؤدي إلى انحراف استجابة الناتج. يتيح بحثنا التنبؤ بسلوك درجة الحرارة، ويسهل تحسين الجهاز، ويوصي بتقليل الجهد التطبيقي للتخفيف من تأثيرات التسخين الذاتي في مستشعرات الضغط المقاومة للانقسام. ويعمل هذا البحث على تحسين فهم تأثيرات درجة الحرارة في مستشعرات الضغط المقاومة للانقسام، مما يتيح التنبؤ والتخفيف من التسخين الذاتي. يؤدي تحسين هندسة الجهاز ومصادر الجهد إلى تقليل تأثير درجة الحرارة على أداء أجهزة الاستشعار.