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Multifunctional Micro- Electro Mechanical Sensor

A Project

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BY

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الخلاصة

يتطلب العالم من حولنا مراقبة البيانات وجمع المعلومات من الطبيعة حيث تلعب أجهزة الاستشعار دورًا رئيسيًا في هذه العملية. عندما يتم تطبيق محفز على جهاز استشعار ، يولد جهاز الاستشعار إشارة كهربائية كاستجابة لهدا التحفيز. تعادل إشارة التيار أو الجهد الخارج الكميات المدخلة. يمكن تحويل كل نوع من الإشارات إلى إشارة كهربائية بواسطة المستشعر ، والذي يمكن أن يأخذ مجموعة متنوعة من الإشارات، بما في ذلك الفيزيائية والكيميائية والبيولوجية. لقد لفت تطوير تقنية النظم الكهروميكانيكية الصغرى (MEMS) اهتمامًا خاصًا لتصميم المستشعرات بالمقايس الصغرى حيث يمثل الحجم واستهلاك الطاقة ودقة القراءة المعلمات الرئيسية التي يجب مراعاتها أثناء تصميم أي مستشعرات جديدة.

في هذا العمل ، تم تصميم ومحاكاة مستشعرات متعددة الوظائف حيث تم اقتراح قياس الرطوبة والضغط كدالة للسعة. كانت فكرة هذا التصميم هي الانتقال من وضع الاستشعار الواحد إلى الاستشعار متعدد الأوضاع لتقليل الحجم واستهلاك الطاقة وتحسين البيانات المجمعة.

تم تصميم انموذجين من أجهزة الاستشعار (بعدين وثلاثة أبعاد) ، وأجريت المحاكاة لقيم مختلفة للضغط المطبق والرطوبة النسبية. كشفت النتائج عن زيادة معنوية في السعة المحسوبة مع زيادة الضغط المطبق للانموذج ثلاثي الأبعاد وكانت أعلى من الزيادة في السعة للانموذج ثنائي الأبعاد. فيما يتعلق بالرطوبة النسبية ، فإن تغيير السعة المحسوبة مع تغيير الرطوبة النسبية له تأثير ضئيل مقارنة بتغير الضغط. وتم استخدام برنامج COMSOL Multiphysics في تصميم ومحاكاة نماذج المستشعرات.

التغيير في السعة هو من 157 بيكو فاراد إلى 173 بيكو فاراد مع زيادة الضغط إلى 100 بار في النموذج ثنائي الأبعاد بينما كان من 2.4 بيكو فاراد إلى 13.9 بيكو فاراد في النموذج ثلاثي الأبعاد مع زيادة الضغط إلى 11 بار فقط. في حين أن تغيير السعة المحسوبة مع تغيير الرطوبة النسبية من 0.1 إلى 0.8 له تأثير ضئيل مقارنة بتغير الضغط. تم استخدام برنامج COMSOL Multiphysics 5.5 في تصميم ومحاكاة نماذج المستشعرات

Abstract

The world is being required monitoring data and gather information from nature where sensors play the major part in this process. When a stimulus is applied to a sensor, the sensor generates an electrical signal as a response. A current or voltage output signal is equivalent to the input quantities. Developing of Micro-electro-mechanical systems (MEMS) technology has drawn a specific attention about designing sensors in the micro scale where the size, power consumption, and accuracy of reading are the main parameters that are required to be considered during the design of any new sensors.

In this work, a multifunctional sensors has been designed and simulated where it has been proposed to measure humidity and pressure as a function of capacitance. The idea of this design was to move from the one mode sensing to a multi-mode sensing to reduce the size, and power consumption and enhanced the collected data.

Two models of the sensor were designed (2 dimensions and 3 dimensions), and the simulation was carried out for different values of applied pressure and relative humidity. The results have revealed of a significant increase in the computed capacitance with increasing the applied pressure for the 3D model and was higher than the increase in the capacitance of the 2D model.

The change in the capacitance is from 157 pF to 173 pF with increasing the pressure to 100 bar in the 2D model while it was from 2.4 pF to 13.9 pF in the 3D model with increasing the pressure to just 11 bar. While the change of the computed capacitance with changing the relative humidity from 0.1 to 0.8 has little effect compering with pressure change. COMSOL Multiphysics 5.5 software was used in the design and simulation the sensor models.

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Lists of abbreviations

Abbreviation	Description
ABS	Speed and Braking pressure
AC	Alternative Current
ACES	The Application of Analytical, Computational, and Experimental Solutions
ACRS	Anti-Cushion Restraint System
AFE	Analog Front-End
CA	Charge Amplifier
CNCs	Carbon NanoCoils
CNTs	Carbon NanoTubes
CNC-CNT	Carbon NanoCoil- Carbon NanoTube
DC	Direct Current
2D	Two Dimensions
3D	Three Dimensions
EMF	Electromotive Force
FSI	Full-Scale Input
FSO	Full-Scale Output
IA	Instrumentation Amplifier
IC	Integrated Circuit
IV	Integrated Voltage
LDR	Light Dependent Resister
MEMS	Micro Electro Mechanical System
RH	Relative humidity

RTD	Resistive Temperature Detector
Re	Reynolds Number

Lists of symbols

Symobols	Definition
A	Cross section area
a	Constant
A_e	Absolute error
b	Constant
C	Capacitance
D	relating the electric displacement
D_r	the remanent displacement
dB	decibels
d	distance
E	electric field (Young module)
F	Force
F_A	Force of area
k	Constant
M_v	Measured value
m,w	Geometry Characteristics
n	Number of point boundary
P	Pressure
pH_2O	Pressure of water vapor in an air-water mixture
$p^*_{H_2O}$	The equilibrium vapor pressure of pure water
Q	Charge
R	Radius of membrane

RH	Relative humidity
S	The electrical output signal
s	The physical input signal
T	The elasticity tensor of fourth order, denoting the product of two dot tensors (or double contraction)
T_v	True value
u	Displacement field
ν	Poisson's ratio
x,y,z	Characteristics length
σ	Stress tensor
σ_{ext}	External Stress
σ_0	Initial stresses
σ_q	Viscoelastic stress
ε_{inel}	Inelastic strain
ρ_m	The density of the sensing film
ρ_w	The density of water
ε	Dielectric constant
δ	Area and the distance between the plates
ρ	Material density
μ	Poisson's ration
ϵ	Relative permittivity
σ	Electrical conductivity
ϵ	Strian
ε_{el}	Elastic strain
ε_0	Initial strain

ε_{ex}	External strain
ε_{th}	Thermal strain
ε_{hs}	Hygroscopic strain
ε_{cr}	Creep strain
ε_{vp}	Viscoplastic strain

Chapter one

Introduction

1.1 General Introduction:

Sensors are devices that detect and respond to signals or stimuli by detecting signs and producing responses. It is possible to defy the stimulus signals by making use of the measure, attribute, or nation that has been perceived. Also, a sensor may be thought of as a translator, as it translates a nonelectrical quantity into the Electrical signal. A sensor can enter a residence in a variety of ways, and it has a variety of electrical output features. The electrical output will vary slightly in response to little variations in the perceived amount, which may be detected if there is a slight shift in the sensed quantity by their measure capability [1].

All sensors are classified according to the functions they perform, the materials they're made of, and the manufacturing processes they employ. The cost, precision, and/or sensing range of some sensors are also used to categorize them. Passive sensors and active sensors are the two primary types of sensors. When an external stimulus is applied to a passive sensor, it produces an electrical signal in response. To put it another way, the sensor is responsible for converting the energy of the input into the energy of the output signal [2]. There are two principal types of sensors: passive sensor and active sensor. A passive sensor does not require any extra power source and electric powered signal is produced immediately in reply to stimulus of external sources. This skill that the sensor converts input strength to output signal electricity. Examples of passive sensors include photographic, thermal, electric powered field sensing, chemical, infrared and seismic. The active sensors need external sources of electricity for their response, known as excitation signal. To produce the output signals, sensors undertake essential modifications to these enter signals. The lively sensors are additionally recognized as parametric sensors due to their personal residences which can be modified in response to an exterior impact and these homes can be later on modified into electric signals. Active sensors have a variety of purposes related to meteorology and statement of the Earth's floor and atmosphere:[3].

Variation mechanisms, analogue and digital sensors, as well as other sensor types, are all dependent on their detection characteristics to function properly. There are a lot of sensors that can be used for many different things. For example, photoelectric, thermoelectric, electrochemical and electromagnetic sensors are all examples of sensors that can be used for a variety of purposes. Sensors with discrete features and digital outputs are distinct from sensors with analogue features and analog outputs. A continuous output signal is provided by an analog sensor, i.e., a signal that is proportional to the measured amount . Sensors can also be categorized based on their ability to detect [4].

1.2 what is a sensor ?

It is a type of electronic device that is capable of receiving a wide range of signals such as physical, chemical, or biological signals and converting them into an electrical signal. In other words, after receiving a signal or stimulus, a sensor reacts by producing an electrical signal in response to the stimulus received by the sensor [5]. The output signals relate to certain types of electrical signals, such as current and voltage that are generated [2].

1.3 Why sensors are used ?

Sensors have the capacity to measure a wide range of data about the processes going place within a system, which opens the door to a plethora of potential applications [6].

The data collected by sensors can be utilized for a variety of purposes, including:

1. Keeping the system running as effectively as possible.
2. Keeping an eye out for any anomalies during the operations.
3. Maintaining control over the processes.
4. Making efficient use of available resources.
5. Making design modifications in order to boost performance even further.
6. Expansion of the product line in the future.

Example, a temperature sensor installed in a furnace periodically detects the temperature and transmits the data to the control unit for further processing. If the temperature exceeds a preset limit, the intelligence of the regulating unit has the ability to turn off the furnace's power supply, preventing harm.

1.4 Top sensor applications:

Sensors are employed in a wide range of fields, including the Automotive, Manufacturing, Aviation, Marine, Medical, Telecommunications, Chemical, and Computer hardware industries, among others. We will take a closer look at some of the sensors employed in these fields [7].

1.4.1 automotive:

Listed below are some sensor-related automobile uses:

1. **Traction control and Braking:** System of braking with Antilock Braking System (ABS) speed and braking pressure is measured by sensors attached to a

steering wheel and sent to the ABS control system on a continuous basis. In response to the driver applying the brakes suddenly, The ABS system releases braking pressure to prevent the vehicle from skidding or locking its wheels, based on data from sensors about brake pressure and velocity. It is one of the most important parts of a vehicle's overall safety.

2. Air Bags – Anti Cushion Restraint System (ACRS): Car sensors, such as crush sensors and accelerometers, track the amount of force applied to the vehicle. If the ACRS detects that the force is greater than the upper limit, then it can set off the airbag and save the lives of anyone trapped within if an accident occurs.

3. Avoiding Collisions: Front, rear, and side proximity sensors alert the driver to a possible accident. Infrared, video, and ultrasonic technology help drivers park their vehicles in small spots.

4. Comfort and Convenience: vehicle speed, engine speed, fuel level, tire pressure, doors/decks, and light bulbs are the sensors that keep drivers informed and alert while they are behind the wheel.

5. **Engine Data:** In addition to ignition, combustion, oxygenation of exhaust gas, mixture of fuel, and recycling of exhaust gas, sensors also give a wealth of information about engine performance.

1.4.2 Manufacturing

The following are a few examples of sensor-based manufacturing processes [8]:

1. Machines and assembly equipment may be serviced using data from sensor in the machines.
2. On the basis of sensor data, continuous monitoring of machine performance and effective reorganization of processes are carried out.

3. Fine-tuning quality systems with sensor data and raising quality standards are some of the goals.
4. As a result of a decrease in quality and process requirements, the design should include warnings and alarms.
5. Ability to respond quickly to changes in the marketplace.

1.4.3 Aviation

Aircraft navigation, system monitoring, and instrument control are all handled by sensors in the aviation sector. Flight operations, aircraft performance, and design changes may all benefit from this data. To name a few, these sensors include tachometers, oil-and-fuel level gauges, altimeters, and airspeed meters. To handle the general operation and emergency circumstances, the pilot uses sensors to assess the ground conditions, vibration, and other environmental elements [8].

1.4.4 Medical & Healthcare

Doctors use signals generated by sensors in medical equipment, surgical tools, and gadgets for a wide range of reasons, including diagnosis, therapy, and control functions, among other things [9].

Among the uses are:

1. The monitoring of blood pressure (self).
2. Individuals who check their glucose levels on a continuous basis.

Automatic measurement of the patient's vital signs and transmission of the data to the doctor.

3. Increased availability of ambulatory and home care therapies.
4. Detection of visitors who are passing illness to patients in hospitals through the use of automated technology.

5. Laboratories that are decentralized.
6. The use of robots in the Operation Theater.

1.5 Literature review:

In 2003, Houri Johari [10], created a piezoresistive pressure sensor and a capacitive humidity sensor to function in the ranges of 0 to 2 atm and 0% to 100%, respectively. Along with a polysilicon resistor temperature sensor was investigated, which can operate between –50°C and 150°C. The sensor's multimeasurement capacity makes it ideal for point-by-point mapping of environmental variables for enhanced process control. For the pressure, relative humidity, and temperature sensors, the author presented results based on the application of analytical, computational, and experimental solutions (ACES) technique, which is particularly appropriate for the creation of MEMS sensors.

In 2011, R. Karthick et al. [11], presented a capacitive humidity sensor model that predicts how the sensor will react to changes in humidity ranges that can be used for breath analysis. Based on molecular diffusion, COMSOL Multiphysics® was used to simulate how the dielectric polymer film on the electrodes would move.

In 2012, G. Mishra et al. [12] used Comsol Multiphysics to show how to make a MEMS-based capacitive pressure sensor. The design shows how different structures bend or twist, and it shows where stresses and displacements.

In 2016, Jagadish et al. [13] designed MEMS sensor which has the ability to sense and control environmental parameters such as temperature, pressure, humidity etc.

The main motivation of this work was the necessity in the fields of automotive industry, climate control, data loggers and humidity monitoring. The capacitive and humidity sensor is designed and analyzed in MEMS technology using COMSOL Multiphysics. The sensor consists of two metal armatures between which a layer of insulating polyimide is sandwiched.

In 2018, M. N. Ismail1et al. [14] simulated a moisture sensor using hybrid MEMS technology to combine electronic, electric and mechanical components in a micron-size system. This paper talked about a simulation study of a typical moisture sensor made with a Tungsten Inter-Digitized (TID) MEMS device. The moisture sensor was made based on the material and physical dimensions and layout of the current material.

In 2020, Yuyu Gao et al. [15] showed a flexible multifunctional piezoresistive pressure sensor based on microchannel-confined MXene. As a result, extrinsic forces will cause the distance between separate MXene and neighboring interlayers to decrease to variable degrees, resulting in proportional resistance variations. This work attempted to solve a lot of problems by bringing new features such as small limit detection (of 9 Pa), large Sensitivity (99.5 kPa1), and a quick reaction (4 ms).

In 2021, Chengwei Li et al. [16] used an all-carbon sensing media to build a simple and low-cost sensor that can measure strain, temperature, and humidity separately. Additionally, they demonstrated that several stimuli may be detected simultaneously using the sensing advantages of Carbon NanoCoils CNCs and Carbon NanoTubes CNTs working together. Motion detection, pulse
wave monitoring, and breathing monitoring are just a few of the things the Carbon NanoCoil- Carbon NanoTube CNC-CNT-based sensor can do well. It can also be used to detect multi-mode vibrations (for smart carpets) and weigh light objects.

1.6 Aim of work

1. The work is aimed to design and simulation of MEMS humidity and pressure capacitive sensor that employ an elastic pressure-sensing element in the form of a changeable capacitor gap, which is caused by the displacement or deflection of a moveable membrane-electrode relative to a fixed electrode under pressure. The basic functionality of these pressure & humidity sensors is based on a change in capacitance as a result of a load applied to one of the electrodes.
2. Such a sensor is considered multi-physical system which involves electrostatics and mechanics of solids this will move the sensing principle from traditional single mode to multi-mode sensing to reduce the size, power, cost and enhance the measurements

1.7 Thesis outline

This thesis comprises of five chapters as follows:

- Chapter one : an introduction about the research topic and literature review with the aim of work has been presented.

- Chapter two: a background and all the mathematical behind the proposed work and what related to design the sensor are introduced.

- Chapter three: The proposed model and designing the sensor using COMSOL is presented.

- Chapter four: The simulation results that were obtained from COMSOL software and discussing the results are shown for 2 D and 3D cases.

- Chapter five: conclusions and future research directions are drawn.

Chapter Two

Theoretical Background

Basic concepts on humidity, water vapor, relative humidity, and force of pressure are introduced in this chapter to illustrate the essential theoretical features of the sensing in Micro-electro-mechanical systems (MEMS).

2.1 Water Vapor

Vapor is water in its gaseous state. It is a particular state of water found within the hydrosphere. It is possible to create water vapor by either evaporating or boiling water (or by melting ice). Water vapor, like the majority of the constituents of the atmosphere, is transparent. Water vapor is continuously generated and removed from the atmosphere under typical atmospheric conditions. Convection currents can be triggered by air that is less dense than the surrounding air [17] .

Figure (2.1): (a) sensor (b) water vapor

As a greenhouse gas and a feedback mechanism for global warming. It contributes more to total greenhouse gas emissions than non-condensable gases such as carbon dioxide and methane, which are not a component of the hydrosphere or hydrologic cycle. Since the industrial revolution, steam has been used extensively in cooking and in the generation and transportation of energy [18].

2.1.1 Properties

Evaporation: A water molecule is considered to have evaporated when it departs a surface and dissipates into the adjacent gas. At the molecular level, the process by which water molecules move from one state to another is called kinetic energy release or absorption. The term "thermal energy" refers to the total amount of kinetic energy transferred. Which occurs only when the water molecules temperatures differ. Evaporative cooling is the process through which water vapor loses heat as it evaporates. The frequency at which molecules return to the surface is determined by the amount of water vapor in the air. Net evaporation results in a cooling of the water body because of the resulting loss of heat energy [19].

Figure (2.2): Evaporation

Atmospheric conditions impose limitations on evaporative cooling. When we talk about humidity, we're talking about how much water vapor there is in the air.

Devices called as hygrometers are used to measure the amount of water vapor in the air. Specific humidity or relative humidity percentage are the most used units of measurement. The equilibrium vapor pressure is defined by the temperature of the atmosphere and the water surface; When the equilibrium vapor pressure is reached, the partial pressure of water vapor equals 100 percent of the relative humidity [20]. The term "full saturation" refers to this state. Dry air has a relative humidity of 0 g/m^3, while saturated vapor at 30 °C has a relative humidity of 30 g/m^3 (0.03 ounce/cubic foot).

2.1.2 Condensation: When the temperature of a surface falls below the dew point or when the air's water vapor equilibrium is disrupted, condensation occurs. water vapor condenses onto that surface. A net increase in temperature happens when water vapor condenses on a surface. Warmth can be carried by a molecule of water. As a result, the air's temperature slightly decreases. In the atmosphere, condensation generates rain, fog , and clouds (Typically, only when cloud condensation nuclei facilitate the process). The dew point is the temperature at which water vapor in the air condenses before it can condense [21]. Cloud droplets are formed when moisture in the air condenses.

Figure (2.3): Condensation

2.2 Humidity

The amount of water vapor in the air is known as humidity. When water is in its gaseous state, vapor can't be seen by the naked eye. Dew or fog are more likely to form if the air is more humid. As the temperature and pressure of a system rises or falls, so does humidity. There is more humidity in chilly air than warm air because of the same amount of water vapor being released. The dew point is a related metric. Absolute, relative, and specific measures of humidity are the three most commonly used units [22].

It is possible to represent absolute humidity in grams per cubic meter of moist air or grams per kilogram of dry air (usually in grams per kilogram).

Percentage measures how much more or less humid the air now is in comparison to the maximum humidity that would be present at that temperature.

To put it another way, the specific humidity measures how much water vapor mass is in relation to that of the moist air parcels.

2.3 Relative humidity

The relative humidity(RH or ϕ) is the partial pressure of water vapor in an air-water mixture where is measured and expressed as a percentage(pH_2O) in the mixture to the equilibrium vapor pressure of water|(p^*H_2O) pure water on a flat surface at a specific temperature:

$$\phi = \frac{p_{H_2O}}{p^*_{H_2O}} \qquad (2.1)$$

Basically, at a particular temperature, the amount of water vapor in the air may theoretically hold is known as "relative humidity.", and vice versa. The air temperature has an effect on it: It's possible that cooler air might carry less water vapor, hence cooling it can result in the condensing of water vapor. Temperature increases may also cause fog to dissipate because the air between the water droplets becomes more capable of storing water vapor as it warms. As a result, even while the absolute humidity remains constant, a change in air temperature might alter the relative humidity. Only water vapor is taken into account when calculating relative humidity [23].

Relative humidity is not affected by mist and cloud formation, but their existence can indicate that the air is close to the dew point; this is why they are not included in this measurement.

$$Relative\ Humidity = \frac{actual\ vapor\ density}{saturation\ vapor\ density} \times 100\% \qquad (2.2)$$

reducing the humidity by removing some of the vapor

2.4 Useful equations for sensors

Sensors can be classified according to the values of a number of critical variables. The following are some of the most important properties of sensors:

2.4.1 Transfer function

By using the transfer function, one can see how the physical input signal or stimulus (r) and the electrical output signal (R) are related. Different types of nonlinearity, such as logarithmic, exponential, or power functions, are possible in this function based on the relationship between input and output [18–20]. Unidimensional function is used in most circumstances, which indicates that the relationship between the output and input is determined by one stimulus [24]. This linear relationship is depicted as:

$$S = a + b(s) \quad (2.\ 3)$$

where a is the intercept used by the output signal at zero input signal and b is the slope, also called sensitivity S. Depending on the properties of sensors, this can be amplitude, frequency or phase. It is sometimes referred to as the sensor's output. Some examples of non-linear functions:

Logarithmicfunction: $\boldsymbol{S = a + b\ln s}$ (2.4)

Exponential function: $\boldsymbol{S = ae^{ks}}$ (2.5)

Power function: $\boldsymbol{S = a_0 + a_1 s^k}$ (2.6)

where k is constant

Some sensors may not meet the aforementioned requirements, and in these circumstances, higher-order polynomial approximation is necessary.

2.4.2 Full-Scale Input (FSI)

Difference between maximum and minimum input stimulus values expressed in decibels is what this term refers to (dB). Logarithmic ratios of power or force to voltage are also used in this measurement. Force, current, and voltage are all converted to decibels by multiplying their logarithmic values by 20.

$$dB = 20 \log \frac{s_2}{s_1} \quad (2.7)$$

where s_2 and s_1 are the maximum and minimum values of input, respectively.

2.4.3 Full-Scale Output (FSO)

When the maximum and minimum input stimuli are provided, the electrical output signals full-scale output shifts between their maximum and minimum levels. Additionally, the FSO incorporates all of the deviations from an ideal transfer function.

2.4.4 Accuracy

Sensors' accuracy, or the difference between the recorded value and the real value, is a crucial property quantified in terms of measurement error. Percentage of full scale or percentage of reading is used to indicate it. A sensor's accuracy rating is based on a variety of factors, including variance, linearity, calibration, repeatability errors, deadband, and so on [25].

Absolute error = | Measured value - True value | $A_e = | M_v - T_v |$ (2.8)

2.4.5 Calibration

There are many sensors available but to get the best possible sensor with optimal value of accuracy, the sensor needs to be calibrated in the device where it will be used. It is an adjustment or set of adjustments made on a sensor or device to make that device function accurately and error free. For instance, we have to measure the pressure with an accuracy ± 5 pa, and a given sensor is rated with an accuracy of ± Advances in Modern Sensors 10 pa.

The calibration error is actually a type of inaccuracy which is accepted by manufacturers during the time when the devices or sensors are calibrated in the factory. This obtained error is not uniform and can change during the process of calibration [26].

2.4.6 Hysteresis

Material hysteresis occurs when a material's frictional and structural characteristics alter over time. A sensor's hysteresis error, seen in Figure (2.4), is the difference between two output values that correspond to the same input. It is possible to express the amount of hysteresis mistake as a percentage of the given pressure range. For half of the pressure reference point range, this hysteresis error may be identified [27].

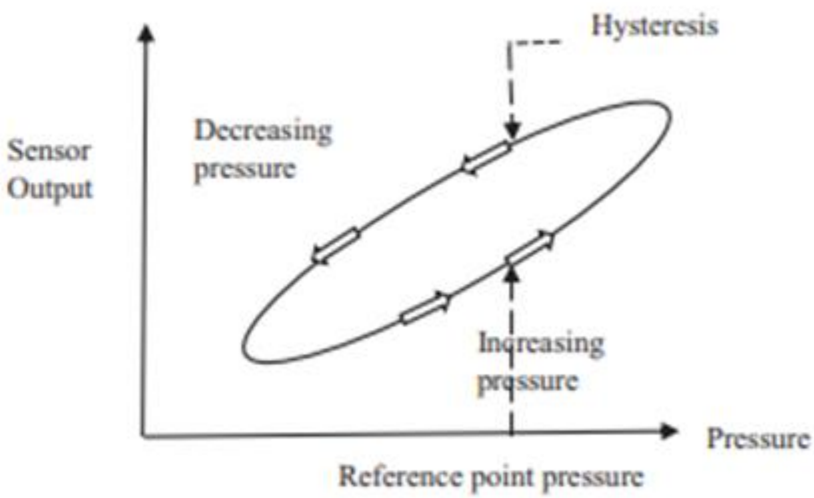


Figure (2.4): Hysteresis[27]

2.5 Capacitance

2.5.1 What Is Self-Capacitance?

A system's capacitance measures how well it can hold onto electrical charge. The amount of charge required to elevate a body's electric potential by one volt in comparison to a grounded reference potential can be used to describe it. If the system is linear, then

$$\boldsymbol{Q = C.V} \qquad (2.9)$$

There are three components to capacitance: Q (charge), V (potential difference), and C (capacitance).

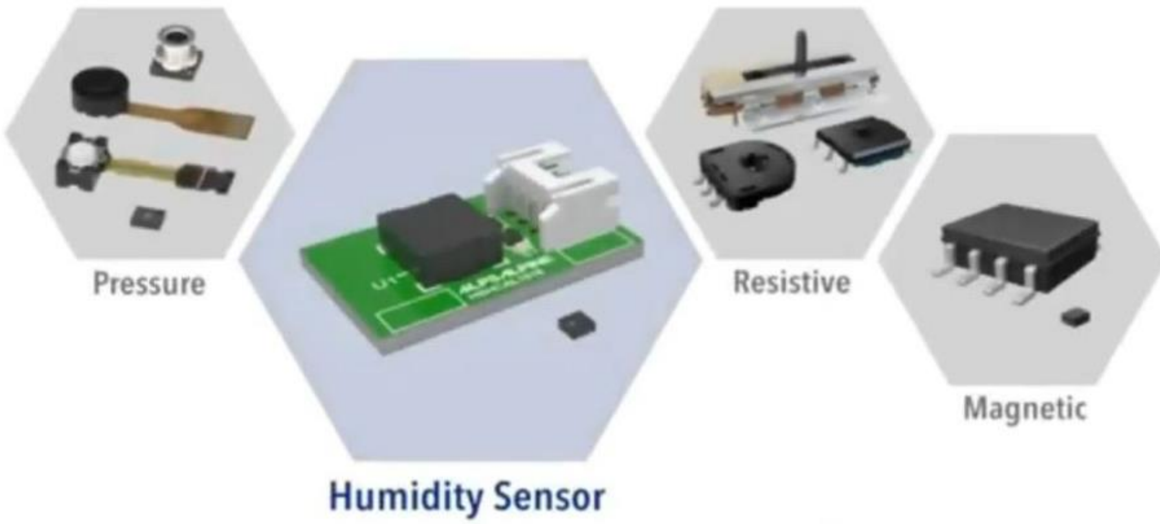
Before we get to multiconductor systems, remember that by definition, even a single isolated conductor has a capacitance, defined relative to a grounded spherical shell at infinity[28]. For the case of a conducting sphere, this self-capacitance is:

$$\boldsymbol{C = 4\pi\varepsilon_0 R} \qquad (2.10)$$

Where R is Radius of membrane

2.6 Types of Sensors:

There are several different types of sensors that are routinely utilised in applications variety [29]. Temperature, resistance, pressure, and heat flow are the physical characteristics of these sensors. In the next section, we'll go through the various types of sensors in more detail. Figure (2.5) shows the types of sensors.



Figure(2.5): type of sensors[29]

2.6.1 Temperature sensors

When an item or system produces energy in the form of heat or cold, a thermal sensor will be used to determine the quantity of created energy. It enables any physical change in that energy to be sensed or detected in that energy and provides an output that can be either analogue or digital in nature. Temperature sensors are employed in a variety of applications, including environmental temperature notification, medical devices, cars, and other similar ones. According to the application and the properties of the sensor, there are several different types of temperature sensors available including contact temperature sensors and non-contact temperature sensors. Contact temperature sensors are used to measure the temperature of an object. In a contact temperature sensor, there is physical contact between the sensor and the item being sensed, and conduction is employed to monitor changes in temperature over time. A wide range of temperatures may be utilized to detect solids, liquids, and gases using this sensor. In a non-contact temperature sensor, we employ the characteristics of convection and radiation to detect temperature changes [30].

In order to generate heat and cold, it utilizes radiant energy.

2.6.1.1 Resistive temperature detector*:* Temperature, as well as resistance, is measured using a Resistive Temperature Detector (RTD), commonly called a resistance thermometer. According to the temperature coefficient of the sensors, it is often constructed of high-purity conducting metals such as copper, nickel, and platinum. These materials are looping together to form a coil, the electrical resistance of which varies in response to a temperature function. The functioning mechanism of a resistance temperature detector (RTD) is quite similar to the functioning mechanism of a thermistor [30].

2.6.1.2 Thermocouple*:* It is used in the measurement of sensors for the detection of temperature fluctuation. The thermocouples are connected by means of two metals that are linked together to form a junction. Consequently, metals have two types of junctions: the hot junction and the cold junction, which is also known as the measurement junction and the reference junction, respectively. As a result of the change in EMF (electromotive force) caused in a thermocouple and the output voltage acquired by using the relationship between voltage and temperature, these junctions are maintained at different temperatures. As a result of the temperature differences between the two junctions, a voltage is created across the junction, which is then utilized to measure the temperature sensor. The Thomson effect, the See beck effect, and the Peltier effect are the three main effects that the thermocouple is founded on. It has the widest temperature range of any of the temperature sensors, spanning from 200 degrees Celsius to 2000 degrees Celsius [30].

2.6.2 Pressure sensor

In unidirectional portions of a surface, pressure is defined as an external force placed on it. Pressure gauges are frequently used to measure the pressure of various gases and liquids. Monitoring and recording pressure is carried out by using a pressure sensor, also known as a transmitter as it turns pressure into an electrical signal. The strain gauge-based pressure sensor is the most commonly encountered form of the pressure sensor. The strain gauge must first be physically deformed, which is connected to the pressure sensor diaphragm before it can be converted. The strain will result in an increase or decrease in electrical resistance that is proportionate to the pressure applied. The change in voltage is a result of the change in atmospheric pressure. The usage of a pressure sensor may be expanded to include monitoring other elements such as fluid or gas flow, speed, water level, and elevation in addition to measuring pressure [31].

2.6.3 Humidity sensor:

Humidity is a measure of the amount of water in the air that is measured by a hygrometer, a device that directly measures the amount of water in the air. Humidity can be transformed from a non-electrical quantity into an electrical quantity by making use of the qualities of resistance, capacitance, and impedance. When it comes to humidity, there are a variety of factors to consider [29]. It is possible to distinguish five different kinds of humidity sensors: resistive hygrometers, capacitive sensors, microwave refractometers, aluminum oxide hygrometers, and crystal hygrometers.

- **Resistive hygrometer:** The main component of a resistive hygrometer is a substance whose resistance changes in response to variations in humidity or relative humidity. The measurement of humidity can be accomplished by using an electrode or a wire that has been coated with lithium chloride (hydroscopic salt). The salt resistance varies with humidity because hydroscopic salt absorbs water and hence has a lower resistance than non-hydroscopic salt.

- **Capacitive hygrometer:** The variations in capacitance of a capacitive hygrometer are responsible for the changes in humidity measured by the device. In a capacitor, a dielectric medium is employed, and the capacitor is composed of two electrodes or plates, with a dielectric medium positioned between the electrodes or plates and between the plates. In addition, there are various hydroscopic materials that display a change in dielectric constant as a function of the relative humidity in the environment. Because of this, the use of a hygroscopic substance or salt in the building of a capacitive hygrometer is possible. Oscillators may produce many frequencies, and a very little change can cause the beat frequency oscillator to generate a new frequency entirely. A heterodyned frequency is produced, and the difference between the two frequencies provides a relative humidity measure.
- **Microwave refractometers:** A microwave refractometers is made up of two chambers, each of which is connected to a Klystron. A klystron is a substance that creates microwaves that have cavities filled with dry air and another cavity filled with a mixture that can be monitored for humidity. Water Advances in Modern Sensors vapour will be present in the mixture, and as a result of the presence of water vapour, the dielectric constant will change, and the frequency of one of the oscillators will change as a result. There is no change in the dielectric constant in the absence of water vapour; therefore its frequency will remain constant. However, when water vapours are present in the mixture, there is an increase in the dielectric constant and thus reducing the frequency. Humidity is measured by the frequency variations in temperature and humidity.

- **Aluminum oxide hygrometer:** In an aluminum oxide hygrometer, aluminum oxide is coated on anodized aluminum, and the dielectric constant of this aluminum oxide varies in response to variations in relative humidity levels. There are two electrodes, one of which is called an "inner" and the other an "outer", the two are formed from a small material, such as gold, and are connected together by a wire. In the inner layer, there are a few pores can be found. The dielectric constant varies as a result of the change in humidity, and this change may be measured to determine the humidity using either the bridge technique or the electric method. The number of mistakes has been significantly decreased, and the reaction time has been cut, resulting in a response that is extremely rapid.
- **Crystal Hygrometer:** Crystals (in a crystal hygrometer) are covered with hydroscopic compounds, which measure moisture content (hydroscopic polymers). Due to the fact that these crystals are utilized as elements to determine the frequency in the oscillator, if the humidity varies, the frequency changes as well, exactly as it does with the capacitive hygrometer. Due to humidity variations in the crystal's mass, which varies in proportion to the quantity of water absorbed by the coating, frequency fluctuations are seen. This variation in frequency is recorded and analyzed. Humidity sensors are utilized in a variety of applications including industrial, agriculture, medicine, and environmental monitoring.

2.7 MEMS technology

This technology incorporates elements of both electrical and mechanical engineering into a single method and approach electronic engineering falls under the umbrella of electrical engineering in this instance. Electromechanical devices use moving components to perform electrical functions [32]. However, the phrase "electromechanical component" is more commonly used to describe devices involving electrical signals or mechanical movements, rather than only manually actuated switches. When a voltage or current may control another, typically isolated circuit voltage or current by mechanically switching sets of contacts, such as in solenoid valves, solenoids can operate a moving linkage, such as in solenoid switches. Although they are electromechanical, piezoelectric devices do not operate according to electromagnetic principles [33]. Electrical signals may be converted into sound or vibration using piezoelectric devices, and piezoelectric signals can be converted into electrical signals using piezoelectric devices.

Electromechanical devices were commonly utilized in complex systems and subsystems before to the introduction of contemporary electronics.

In a capacitive pressure sensor, variable capacitor gaps, caused by membrane electrode displacement or deflection under pressure, are used in as a pressure-sensing element that is elastic. Capacitive pressure sensors have a flat and cylindrical capacitor design, thus this is what it signifies. Due to the capacitance of the capacitor changing in response to the applied pressure, these pressure sensors work in theory.

$$C = \varepsilon 0 \varepsilon \frac{s}{\delta} \quad (2.11)$$

Where:

$\varepsilon 0$ electric constant of the medium between the plates

ε dielectric constant

S / δ area and the distance between the plates.

It is important to be aware of the possibility of dielectric breakdown when the capacitor plates are sufficiently close to one another and when a substantial amount of stress appears, which can damage the membrane. MEMS capacitive sensor simulation has outstanding linearity and a wide working pressure range. Using

Intellisuite software, capacitive sensors may be modeled and simulated in order to enhance the device's design, performance, and manufacturing time. Capacitive sensors have recently surpassed piezo resistive sensors in terms of sensitivity, power consumption, and temperature invariance. It's important to keep an eye on improvements in MEMS capacitive sensor technology as the spectrum of applications grows.

2.7.1 Interdigitated humidity and pressure sensor:

The principle of function of the MEMS moisture and pressure sensor is to create a variable electric capacity of an intern electrostatic system hence the name “Capacitive sensor”. The electric capacity in the case of moisture and pressure sensor varies depending on relative humidity and applied pressure[34]. The idea of the device is to create an electrostatic installation with specific materials that have characteristics which depend on pressure and relative humidity. Many softwares will numerically calculate the electric capacity of the whole system for different values of relative humidity and applied pressure which allows extracting results about variation of relative humidity and pressure [35]. The principals of this type of sensing is shown in Figure (2.6) .

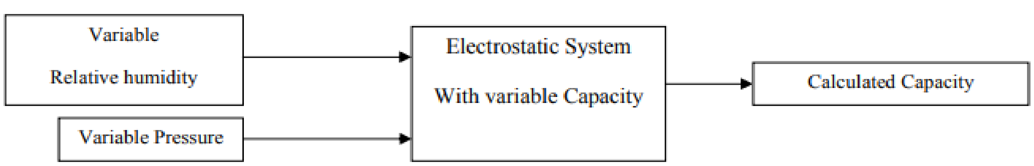


Figure (2.6): Principal of capacitive MEMS humidity and pressure sensor

2.7.2 Influencing capacity using pressure

Variable pressure alters the capacitance of piezoelectric material. Piezoelectric material is a substance that collects electric charge in response to applied mechanical pressure. The piezoelectric effect originates from the linear electromechanical interaction between the mechanical and electrical states in piezoelectric materials. A second benefit of the reversible piezoelectric effect is that materials having this property can generate mechanical strain in response to an applied electric field [39]. Due to the fact that piezoelectric material accumulates electric charges in response to applied pressure, the electrical system's capacitance changes according to the equation (2.9) when using capacitive MEMS moisture and pressure sensors.

Q is the total charge in the electrostatic system, and C is its carrying capacity in Faradays (F). V is the applied electric voltage in Volts (V).

The electrostatic system's capacitance may be altered by varying the system's electric charge, as shown in equation (2.9). This change in electric charge amount is done by the piezoelectric material in response to the applied pressure.

2.7.3 Influencing capacitance by relative humidity:

Sensing film is utilized to study the impact of relative humidity on capacitance. The sensor film is dielectric material with a permittivity which is greatly affected by ambient relative humidity. Therefore, it is feasible to alter the dielectric permittivity of the sensor screen by applying relative humidity. The following equation describes the relationship between the sensing film's change in permittivity and the relative humidity:

$$\boldsymbol{\varepsilon} = (\mathbf{1,6} + \mathbf{1,8Rh}\frac{\rho_m}{\rho_w})^2 \qquad \textbf{(2.12)}$$

Where $\boldsymbol{\varepsilon}$ is the dielectric permittivity of the sensing film (F/m), **Rh** is the relative humidity, $\boldsymbol{\rho_m}$ is the density of the sensing film (kg/m3), $\boldsymbol{\rho_w}$ is the density of water (kg/m3)

The change in the dielectric permittivity will spawn a change in the capacitance of the electrostatic system as it is described by the following expression:

$$\boldsymbol{C = \frac{\epsilon . A}{d}} \tag{2.13}$$

Overall, the capacity of the electrostatic system may be indirectly impacted by the relative humidity by the mean of the sensing film owing to its intrinsic multi-physical characteristic of having a dielectric permittivity which influenced by relative humidity [**38**].

Chapter Three

The proposed model: Design and simulation

In order to design a sensor, the data provided in chapter two must be taken into account. The electrostatic field is generated by connecting two voltage terminals together. The gap between the voltage terminals and the ground terminal is filled with two layers of different material; the first layer is filled with piezoelectric material and the second layer is filled with the sensing film [39]

3.1 COMSOL Model

The proposed work has been designed and simulated in COMSOL Multiphysics software which allows to model the whole suggested sensor and to incorporate all the multi-physical features of the different materials. The user has to define all the objects involved in the system as well as their two- and three-dimensional geometries and also the values of their physical proprieties. In the next sections, the design of the different elements of senor are presented.

3.2 The design of 2D capacitive humidity and pressure sensor

The proposed design is simulated using COMSOL Multiphysics 5.5, which is a general-purpose software platform, based on advanced numerical simulation and using finite element method for physics-based issue modeling and simulation. Coupling of Multiphysics phenomena may be accounted with this software tool. As part of the modeling process, it is essential to go through everything from defining the geometry and physics with conditions to mesh and solve the problem then displaying the results.

3.2.1 Geometry definition

The 2D geometry has a 10 µm width and 10 µm length. It consists a layer of silicon surrounded by air. The center of the model has two electrodes where have been fixed on a sensitive film layer. The electrodes were assumed to be aluminum while the sensitive film was constructed from dielectric material(polymer). A piezoelectric layer was constructed from Lead Zirconate Titanate and fixed under the sensing film layer. After building the geometry and when testing for sensitivity, the instrument is put through its paces in a controlled environment. It is studied in terms of the device's sensitivity to pressure as well as an inducing humidity response to packaging stress. Figure (3.1) depicts the device's geometry. The idea of using a layer of silicon is to keep the electric field inside the sensing area. The humidity and pressure sensor that is included in a silicon device has been connected to voltage terminals and sensing film.

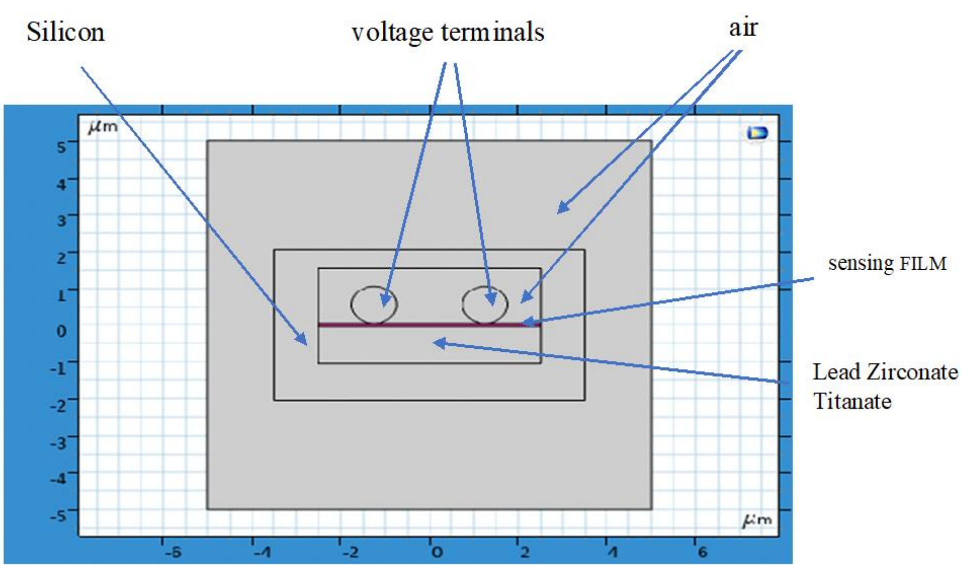


Figure (3.1): 2D geometry definition of the sensor

One volt is applied to each of the two electrodes as a power supply while the terminals of the electrodes are connected to the sensing film by a vacuum which seals the compartment. The piezoelectric layer is connected to the ground. Inside the chamber, the layers on either side form a connection between the two terminals and the sensing film. The sensing layer is used to measure the humidity by sensing the change in the permittivity in between the capacitor while the piezoelectric layer measures the change in the pressure due to the deflection in this layer and consequence the change in the electric field.

3.2.2 Parameters

The parameters used to design this model. Table (3.1) shows parameters of the proposed model

Table (3.1) Parameters of the proposed model

Name	Symbol	Unit	Value
Simulation domain width	Da	[um]	1E-5 m
Electrodes diameter	De	[um]	1E-6 m
Sensing film thickness	e	[um]	1E-7 m
Piezo thickness	Dp	[um]	1E-6 m
Piezo width	L	[um]	5E-6 m
Initial pressure	P0	[kPa]	5000 Pa
Relative humidity	RH		0,5
thickness	Th	[um]	1E-6 m
Thickness sililcon	esi	[um]	1E-6 m
Air density	Rho, _a	[kilogram/m^3]	1.1455 kilogram/m^3
Water density,	Rho, _w	[kilogram/m^3]	997 kilogram/m^3

3.2.3 Materials

The materials were used in the design. Table (3.2) shows materials

Table (3.2) Materials

Material overview	
Silicon (mat1) Domain 2	Domain 2
Lead Zirconate Titanate (PZT-5H) (mat2)	Domain 3
Air (mat4)	Domains 1, 5
Aluminum (mat5)	Domains 6–7
sensing film (mat6)	Domain 4

The voltage terminals have been chosen to have a cylindrical geometry of 1 μm of diameter. The voltage of one terminal is set to 1V and the other terminal is set to -1V. The material from which voltage terminals are made is chosen to be Aluminum. Figure (3.2) shows the Aluminum electrodes, while Table (3.3) indicates the aluminum specification.

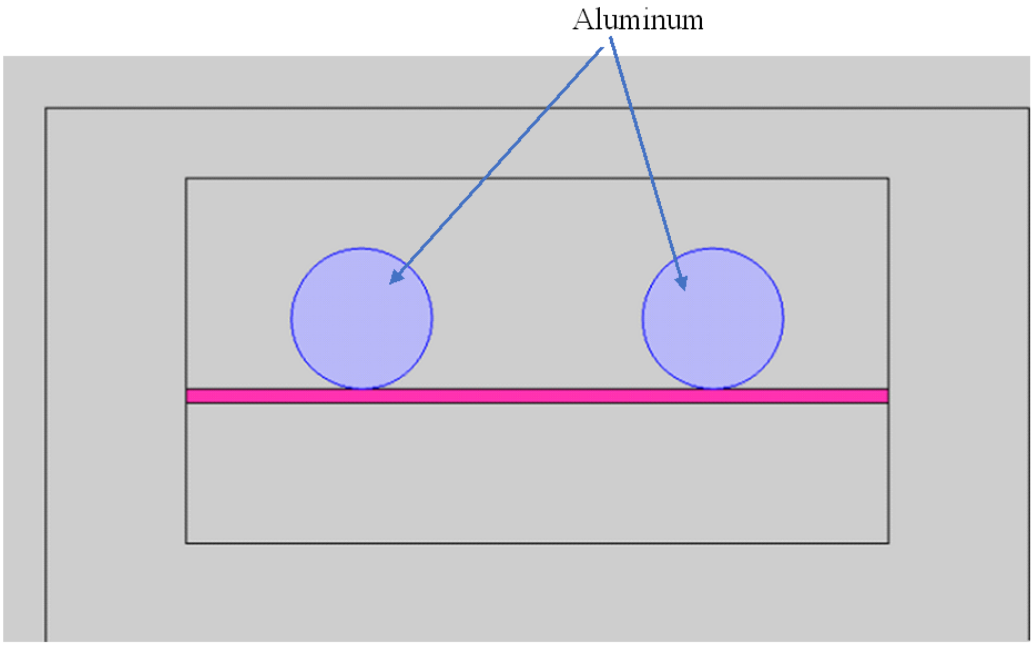


Figure (3.2): Aluminum Terminals geometry

Table (3.3) Aluminum specification

Property	Variable	Value	Unit	Property qroup
DENSTY	Rho,	2700[kilogram/m^3]	kilogram/m^3	Basic
Young'sModulus	E	70*10^9[Paskal]	1	Young'sModulusand and Poisson'sRatio
Poisson'sRratio.	N u.	0.33	1	Young'sModulusand and Poisson'sratio

The cavity or the layer air was also needed and constructed as shown in Figure (3.3). Materials with certain qualities (to determine the relative permittivity) and materials defined by the user are utilized in this region to set the relative permittivity to one (vacuum). The material type of vacuum is non-solid. Table (3.4) shows air layer

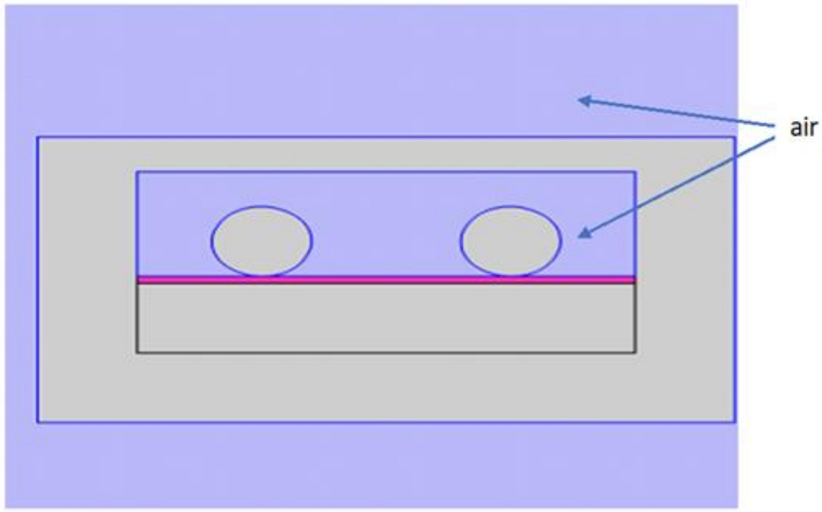


Figure (3.3): The air layer

Table (3.4) air layer

Property	Variable	Value	Unit	Property Group
Rlative permitivty	EpSLONR _iso, EpSLONR = 0	EpS (Hu)	1	Basic,

The layer under the sensing film is shown in Figure (3.4). This material has been chosen to have a rectangular 2D geometry. The material from which the other voltage terminals are made was chosen to be Lead Zirconate Titanate (PZT-5H). All the proprieties of Lead Zirconate Titanate are defined in Table (3.5)

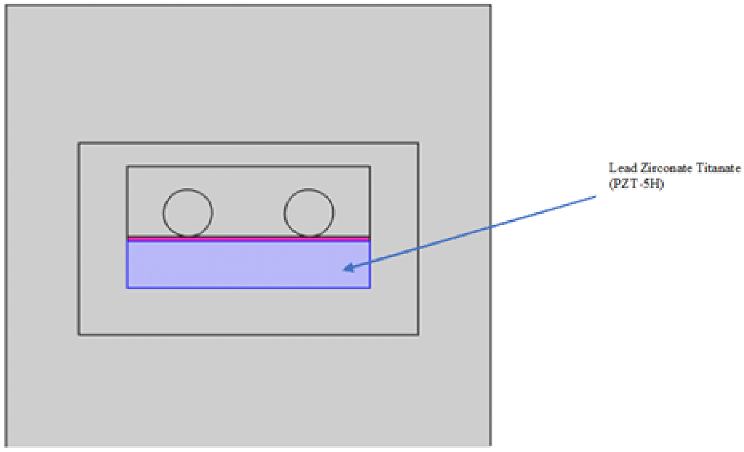


Figure (3.4): Lead Zirconate Titanate (PZT-5H) geometry

Table (3.5) Lead Zirconat e Titanate (PZT-5H) specification

Property	Variable	Value	Unit	Property group
DENSTY	Rho,	1704.4,	kg/m³	BASIC
Elasticity Materix, Voigt Notations	CEij = CEji	1e-9	Pascal	Stress Charge form
Couplings, Materix,Voigt Notations	eEs	C/m^2	c/m²	Stress Charge form
Relative Permitivty	ePsilonrse	1704.4,	1	Stress Charge form

The silicon geometry that encloses all the system has been chosen to have a rectangular 2D geometry Figure (3.5). All the proprieties of silicon are defined in COMSOL Multiphysics and shown in table (3.6).

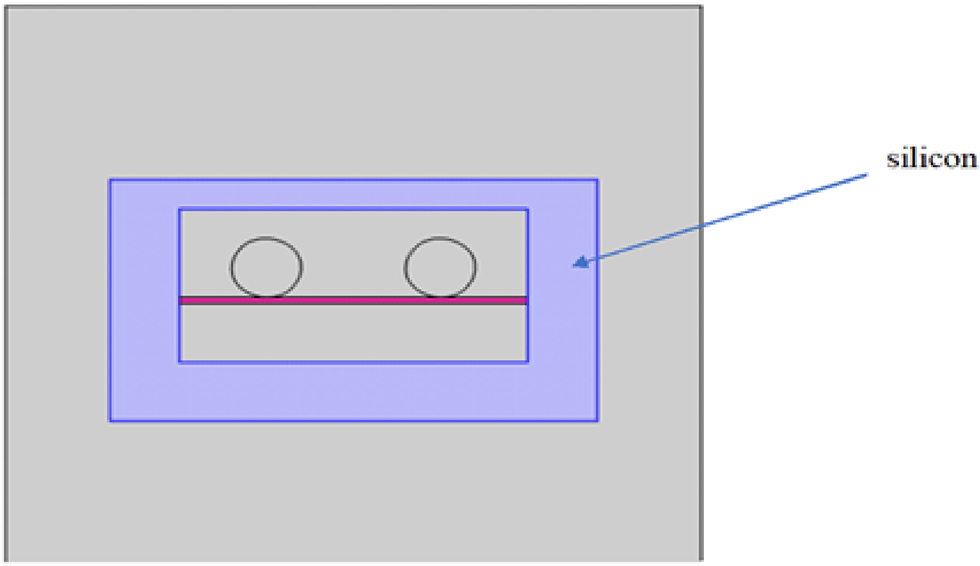


Figure (3.5): Silicon geometry

Table (3.6) silicon specification

Prperty	Varable,	Value	Unit	Propertygroup
RelativePermitivity	Epslonr_iso ; Epslonrii = Epslonr_iso, Epslonrij = 0	11.7	1	BAISIC
Densty	Rho	2329[kilogram/m^3]	kilogram /m^3	BASIC
Young'sModuls	E.	170e9(Pascal)	Pascal	Young'sModulus and Poisson'sRatio
Poisson'sRatio	Nu.	0.28	1	Young's Modulus and Poisson'sRatio

The sensing film layer is constructed as a rectangular 2D geometry and constructed from dielectric material (polymer) and it is used to sense the humidity Figure (3.6) while Table (3.7) sensing film specification.

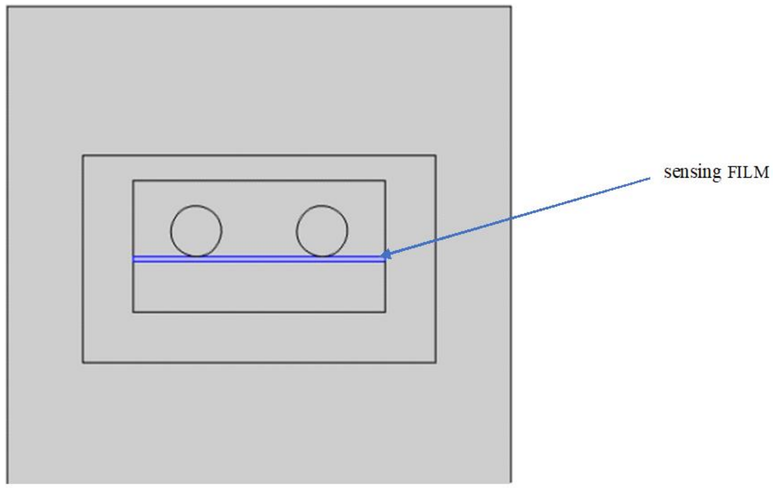


Figure (3.6): sensing FILM geometry

Table (3.7) sensing film specification

Property	Variable	Value	Unit	Propertygroup
RelativePermitivity	Epsilon r= iso, EpsiLon rij = 0	Epsfilm(Rho_a,Rho_w,Hu)	1	Basic,

3.2.4 Specifying physics

After the 2D model of the sensor was constructed, the boundaries of the model have been assumed to specify the physics aspect settings for the electromechanical system. The boundaries include the force due to pressure, the applied voltage and the others suitable boundary conditions. In addition, only linear elastic material at the electromechanical interface can be used to solve structural mechanics equations: By using gauss's law for electric

$$0 = \nabla \cdot S + Fv \quad (3.1)$$

($\nabla \cdot$) is divergence (vector field spacing in 3D world) and it used to calculate the amount of vector electric field

For a linear elastic material, Hooke's law relates the stress tensor to the elastic strain tensor

$$\sigma = \sigma_{ad} + T : \epsilon_{el!}, \epsilon_{el} = \epsilon - \epsilon_{inel} \quad (3.2)$$

$$\sigma_{ad} = \sigma_0 + \sigma_{ext} + \sigma_q \quad (3.3)$$

Here, the stress tensor σ and the strain tensor ε are second-order tensors, while the constitutive tensor T is a fourth-order tensor. The symbol means a contraction over two indice

where (T) is the 4th order *elasticity tensor*, stands for the double-dot tensor product (or double contraction). The elastic strain ε_{el} is the difference between the total strain ε and all inelastic strains ε_{inel}. There may also be an extra stress contribution (σ_{ext})with contributions from initial stresses(σ_0) and viscoelastic stress (σ_q) In case of geometric nonlinearity, the second Piola-Kirchhoff stress tensor and the Green-Lagrange strain tensor are used.

Inelastic strian is equal

$$\epsilon_{inel} = \epsilon_0 + \epsilon_{ext} + \epsilon_{th} + \epsilon_{hs} + \epsilon_{pl} + \epsilon_{cr} + \epsilon_{vp} \quad (3.4)$$

Where Initial strain is ε_0, External strain is ε_{ex}, Thermal strain is ε_{th} , Hygroscopic strain is ε_{hs}, Creep strain is ε_{cr}, Viscoplastic strain is ε_{vp}

$$\epsilon = \frac{1}{2}[(\nabla\mathbf{u})^{\top} + \nabla\mathbf{u}] \quad (3.5)$$

$$\mathbf{C} = \mathbf{f}(E, \nu) \quad (3.6)$$

F is force, **E is** Young’s modulus,

ν is Poisson’s ratio, u is Displacement vector.

The pressure exerted on the diaphragm's upper surface must be represented by applying a boundary load. All boundaries are moving mesh boundary conditions must be used in all cases when the air domain deform and defaulting electromechanical interface boundary condition does not apply. It is determined automatically by the electromechanical interface boundary condition which interface it uses to select from the structural and deforming air domains. Apart from properly applying electrical forces to structural layers, equal deformation of the air domain is also achieved by this method.

3.3. Meshing

Meshing is the process of discretizing elements to solve a set of governing equations throughout the computational Domain.

There are eight types of mesh (extremely coarse, extra coarser, coarser, normal, fine, extra fine, extremely fine). Following the definition, the micro meshing is the following step once the system has been set up with its constants and physical limitations. A mesh throughout for the capacitive humidity and pressure sensor is in accordance with its design and measurements. The number of mesh element of the sensor according to its dimensions. Table (3.8) shows the results of various meshing techniques and Figure (3.7) shows the whole model after meshing.

Table (3.8) Meshing dimensions

Mesh	Finer	Extra Fine	Extremely Fine
Number of Mesh elements	3300	7800	28542

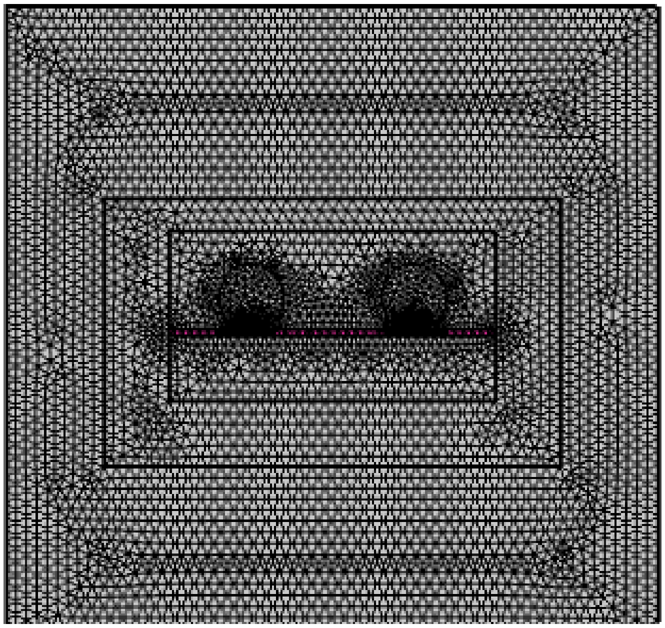


Figure (3.7): Meshing of the geometry

3.4 Capacitive humidity and pressure sensor simulation (3D)

In order to verify our work, a 3D model for the sensor was constructed and modeled using COMSOL Multiphysics software. The 3D model is presented in Figure (3.8). To incorporate all the multi-physical features of the different materials, the design has to define all the objects involved in the system as well as their three-dimensional geometry and also the values of their physical proprieties. In the next section, the declaration and design of the different elements of the 3D senor are presented.

3.4.1 Geometry definition

The 3D geometry has a 10 μm width, 10 μm length and 1×10^4 μm depth. It consists a layer of silicon surrounded by air. The center of the model has two electrodes where have been fixed on a sensitive film layer. The electrodes were assumed to be Tungsten while the sensitive film was constructed from dielectric material(polymer). A piezoelectric layer was constructed from Lead Zirconate Titanate and fixed under the sensing film layer.

After building the geometry and when testing for sensitivity, the instrument is put through its paces in a controlled environment. It is next studied in terms of the device's sensitivity to pressure as well as an inducing humidity response to packaging stress. Figure (3.8) depicts the device's geometry. The idea of using a layer of silicon is to keep the electric field inside the sensing area. The humidity and pressure sensing elements are included in a silicon device.

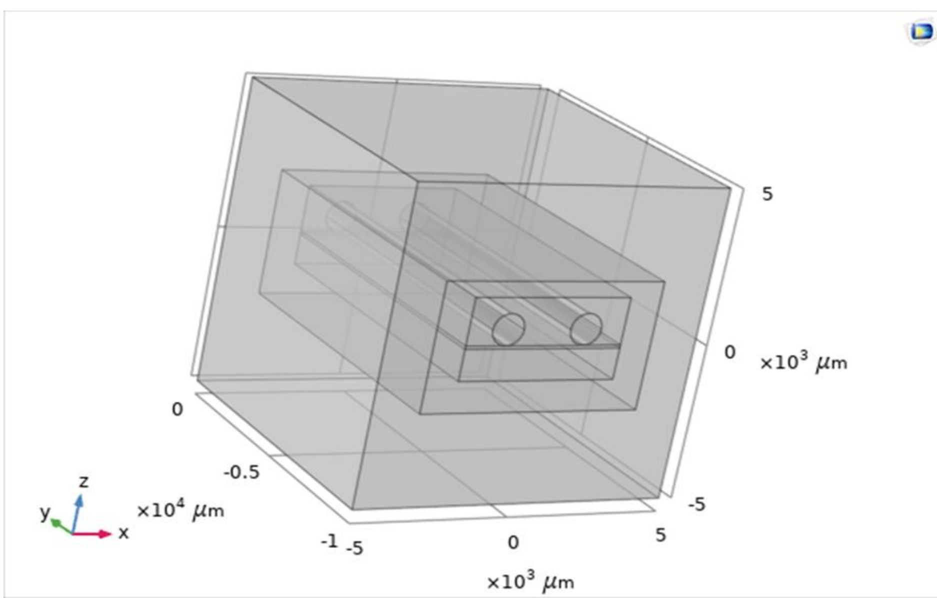


Figure (3.8): 3D geometry of humidity-pressure sensor

One volt is applied to each of the two electrodes as a power supply while the terminals of the electrodes are connected to the sensing film by a vacuum which seals the compartment. The piezoelectric layer is connected to the ground. Inside the chamber, the layers on either side form a connection between the two terminals and the sensing film. The sensing layer is used to measure the humidity by sensing the change in the permittivity of the in between capacitor while the piezoelectric layer measures the change in the pressure due to the deflection in this layer and consequence the change in the electric field. Table (3.9) show this parameter

Table (3.9) The 3D model parameters:

Name	Symbol	Unit	Value
Simulation domain width	Da	[um]	1E-5 m
Electrodes diameter	De	[um]	1E-6 m
Sensing film thickness	e	[um]	1E-7 m
Piezo thickness	Dp	[um]	1E-6 m
Piezo width	L	[um]	5E-6 m
Initial pressure	P0	[kPa]	5000 Pa
Relative humidity	RH		0,5
thickness	Th	[um]	1E-6 m
Thickness sililcon	esi	[um]	1E-6 m
Air density	Rho, _a	[kilogram/m^3]	1.1455 kilogram/m^3
Water density,	Rho, _w	[kilogram/m^3]	997 kilogram/m^3

This model has values that represent inputs to the expressions that describe material attributes, and these values are represented by the symbols. The space between the two terminals is very important part of the sensor because the air flows inside it. Every step of the modeling process, from geometry definition to establishing physics with conditions, meshing to computation to visualizing results will be covered in this section.

3.4.2 materials

Five materials were used to design this model. Table (3.10) shows The 3D model materials

Table (3.10) The 3D model materials

Material overview	
Silicon	Domain 2
Lead Zirconate Titanate (PZT-5H)	Domain 3
Air	Domains 1, 5
Tungsten	Domains 6–7
sensing film	Domain 4

3.4.2.1 Design of voltage terminals

The voltage terminals have been chosen to have a cylindrical geometry of 1 µm of diameter and 10 µm of length. The voltage of one terminal is set to 1V and the other terminal is set to -1V. The material from which voltage terminals are made is chosen to be Tungsten. Figure (3.9) shows the electrodes and Table (3.11) shows the Tungsten specifications.

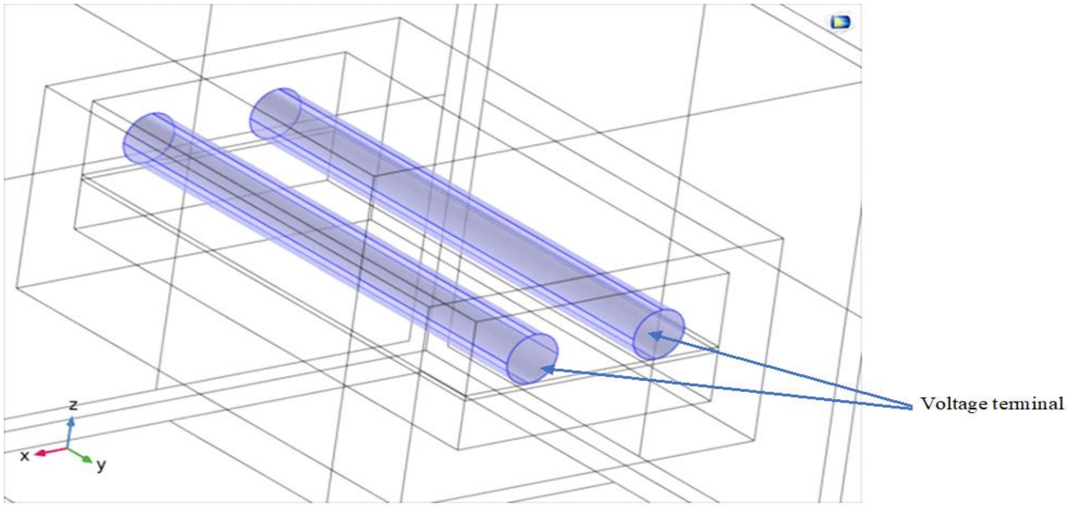


Figure (3.9): Voltage terminal geometry

Table (3.11) Voltage terminal specification

property	variable	value	unit	Property group
Density	Rho,	17800[kilog/m^3]	kilogram/m³	Basic
Young'smodulus	,E	3.6e11[Pascal]	1	Young'smodulus and Poisson'sratio
Poisson'sratio	Nu,	0.28	pascal	Young'smodulus and Poisson'sratio

3.4.2.2 Design of the Piezoelectric material

The Piezoelectric material has been chosen to have a rectangular 3D geometry. The material from which voltage terminals are made is chosen to be Lead Zirconate Titanate (PZT-5H). All the proprieties of Lead Zirconate Titanate are already predefined in COMSOL Multiphysics. Figure (3.10) illustrates Piezoelectric material geometry while Table (3.12) shows Piezoelectric material specification

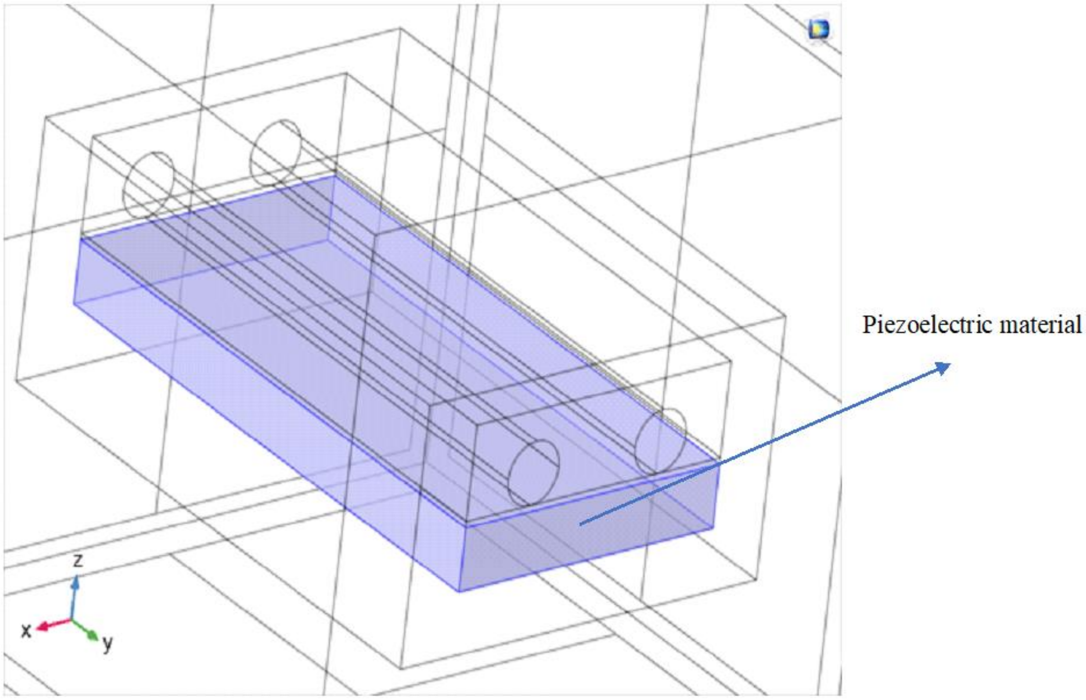


Figure (3.10): Piezoelectric material geometry

Table (3.12) Piezoelectric material specification

Property	Variable	Value	Unit	Property group
DENSTY	Rho,	1704.4,	kg/m³	BASIC
Elasticity Materix, Voigt Notations	CEij = CEji	1e-9	Pascal	Stress Charge form
Couplings, Materix,Voigt Notations	eEs	C/m^2	c/m²	Stress Charge form
Relative Permitivty	ePsilonrse	1704.4,	1	Stress Charge form

3.4.2.3 Design of the sensing film

The sensing film has been chosen to have a cubic 3D geometry. The material from which the sensing film is made is not defined in the software but the program allows to add new materials which are not predefined and to enter manually its physical proprieties. Therefore equation (2.19) was coded manually into the properties of the sensing film. Figure (3.11) depicts the sensing film layer while Table (3.12) shows the layer specifications.

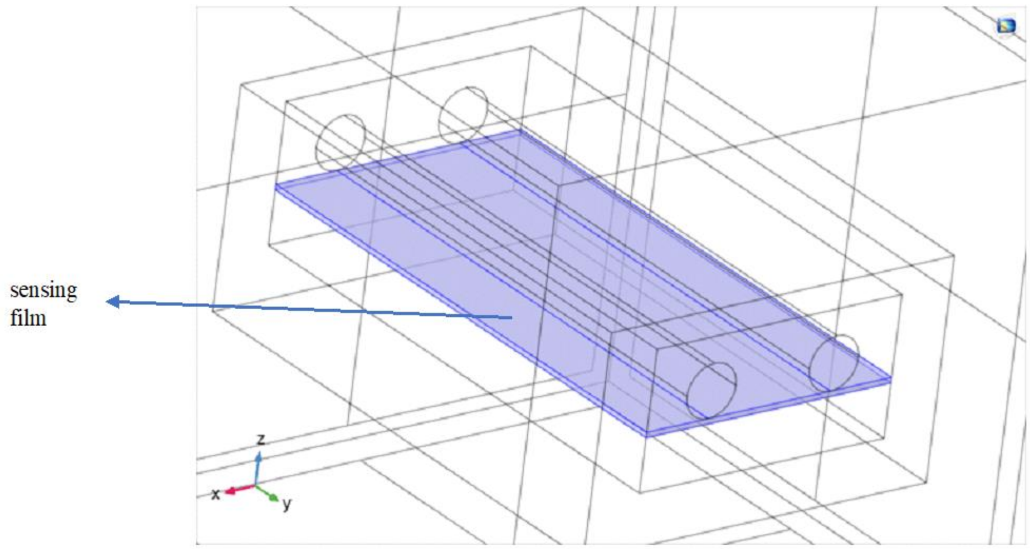


Figure (3.11): Sensing film geometry

Table (3.13) sensing film specification

Property	Variable	Value	Unit	Propertygroup
Relative Permitivity	Epsilonr= iso	Epsfilm (Rho_a,Rho_w,Hu)	1	Basic,

3.4.2.4 Design of the silicon cage

The Faraday cage that encloses all the system has been chosen to have a rectangular 3D geometry (1cm x 10cm x 10 cm). Figure (3.12) illustrates the silicon geometry while Table (3.14) shows the silicon properties .

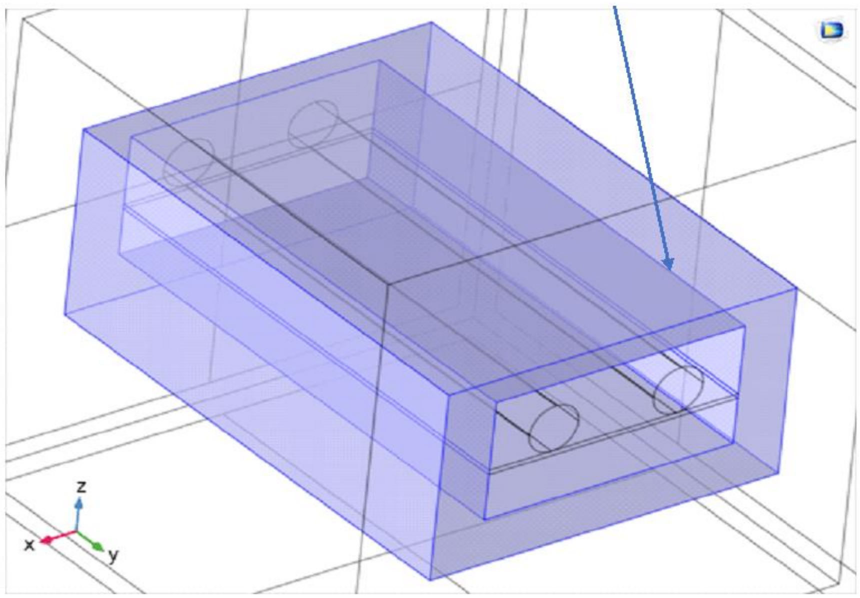


Figure (3.12): Silicon cage geometry

Table (3.14) Silicon cage specification

Prperty	Varable,	Value	Unit	Property Group
Relative Permitivity	Epslonr_iso ; Epslonrii =	11.7	1	BAISIC
Densty	Rho	2329[kilogram/m^3]	kilogram /m^3	BASIC

Young's Moduls	E.	170e9(Pascal)	Pascal	Young's Modulus and Poisson's Ratio
Poisson's Ratio	Nu.	0.28	1	Young's Modulu Poisson's Ratio

3.4.2.5 Air layer

The cavity or the air layer was also added. Materials with certain qualities (to determine the relative permittivity) and materials can be defined by the user are utilized in this region to set the relative permittivity to one (vacuum). The material type of vacuum is non-solid. Figure (3.13) illustrates the geometry of this layer while Table (3.15) shows the layer properties.

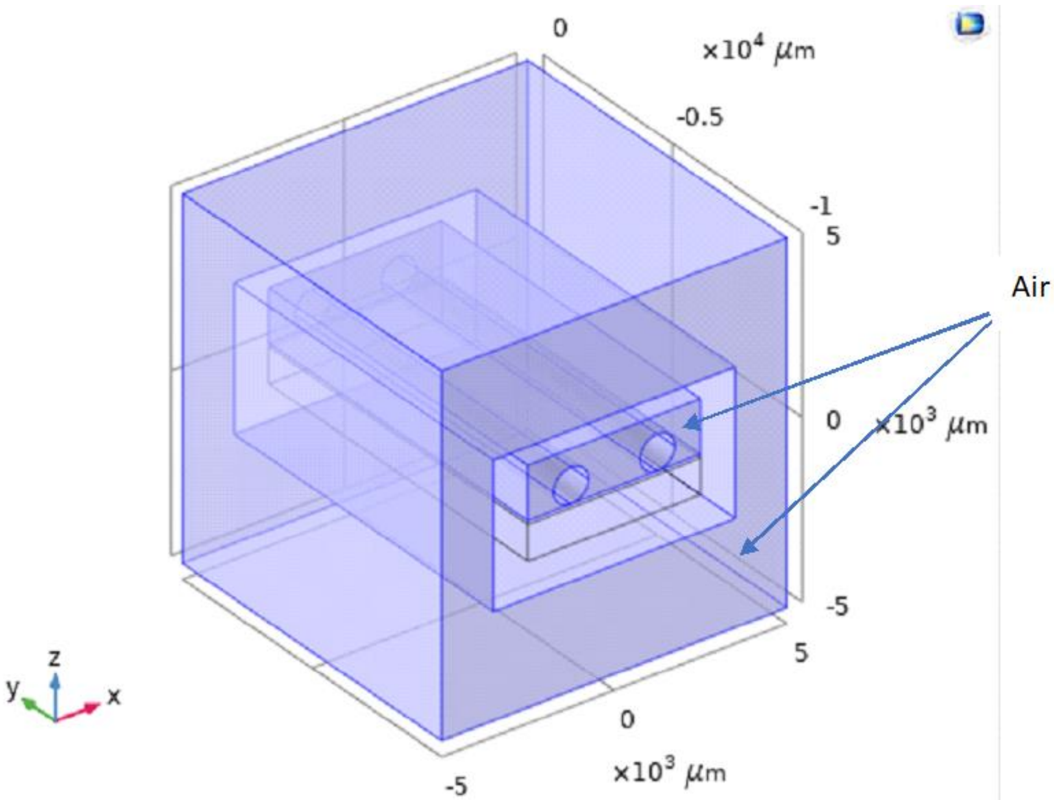


Figure (3.13): Air layer geometry

Table (3.15) Air layer specification

Property	Variable	Value	Unit	Property Group
Rlative permitivty	EpSLONR _iso, EpSLONR = 0	EpS (Hu)	1	Basic,

3.4 Boundary settings

The inputs, outputs, and symmetry boundaries of the silicon cage have been detailed, as have the boundary conditions of the cage itself.

The absolute pressure is one [atm] and the Temperature is 293.15[k]. The total force boundary load is shown in Figure (3.14) and it's given by these equations.

$$\mathbf{S}.\mathbf{n} = \mathbf{F}_A \quad (3.7)$$

$$\mathbf{F}_{A} = -\mathbf{p} \qquad (3.8)$$

Where F_A is force per unit area , and n is number of point boundary

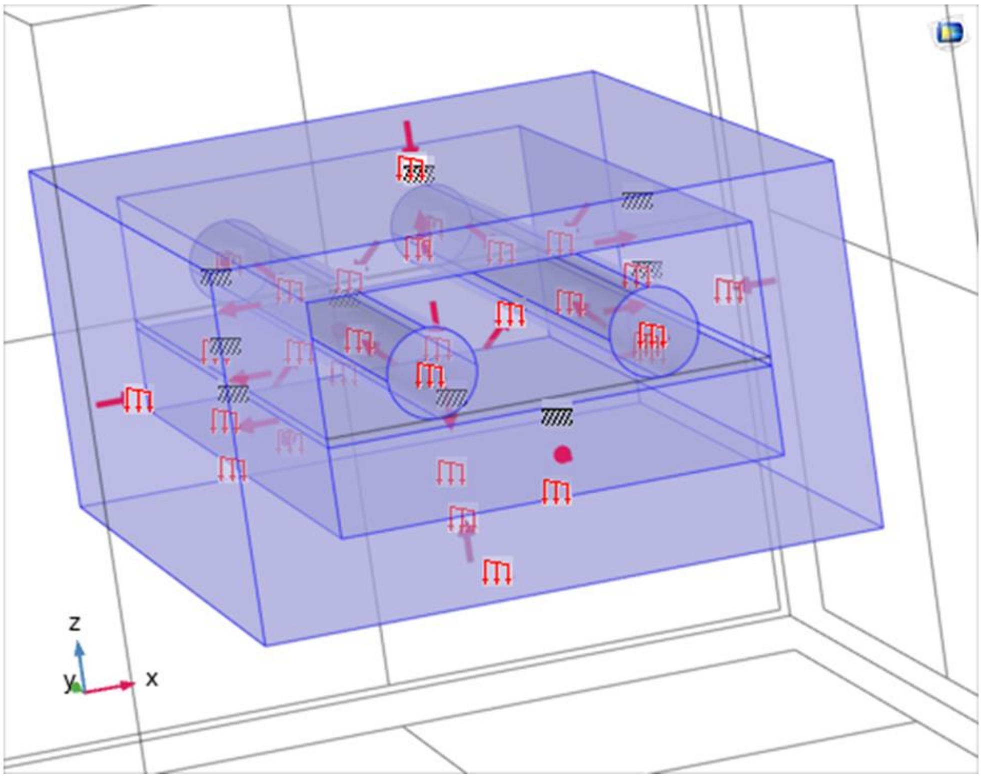


Figure (3.14): The boundary load

3.5 Defining the computing mesh

COMSOL uses Finite Elements methods to do calculation of the capacitance of the system. This numerical method consists of dividing the volume of the system into several 3D blocks and to do iteratively calculation for each block, the division of whole volume of the system into small blocks is called meshing. The software allows the user to choose the meshing of the system to be high, low, or medium meshing. High meshing corresponds to smaller size of element blocks but a big number of them whereas low meshing corresponds to bigger size of element blocks but a small number of them. Choosing the type of meshing affects inversely computing time and calculation accuracy. High meshing takes long computing time and gives more accurate results while low meshing takes less computing time but it gives less accurate results. It is also important to note that computing time depends also on the performance of the microprocessor used. The better is the processor the less is the computing time. This model, medium meshing is chosen which corresponds to dividing the whole system volume which is 100 cm^3 to 21069 element blocks. Figure (3.15) shows the whole meshing of the sensor.

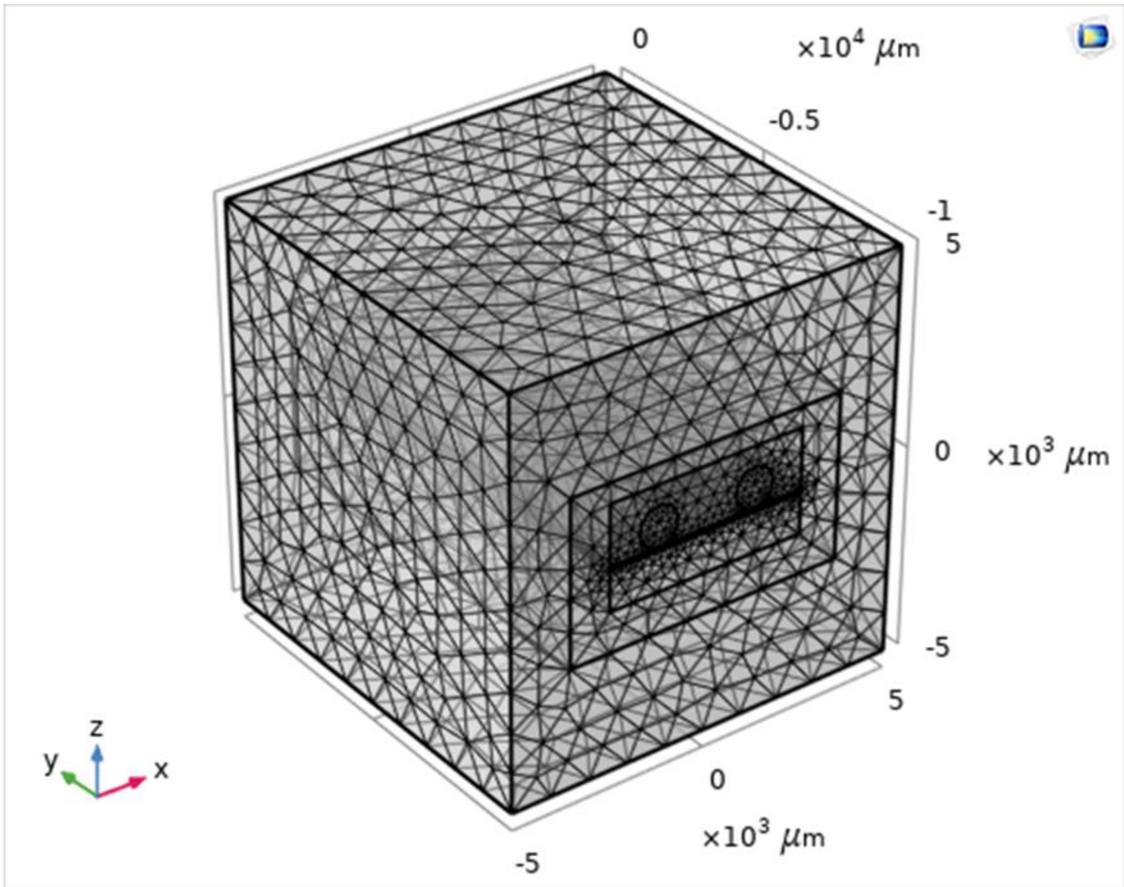


Figure (3.15): System meshing

Chapter four

Results and Discussion

The proposed model that has been described in chapter three was performed using COMSOL for three initial proposed values of pressure and two values of relative humidity. The given capacitances value for the six possible combinations are presented in table (4.1). These proposed values have been assumed according to previous related sensors. The capacitance and pressure values have been used and extended in the simulation of the 2D and 3D models where one of them has been fixed and the second was changed for different cases.

Table (4.1) Obtained capacitance values

P (bar)	RH	C (pF)
1	0.1	1.5552
1	0.6	1.559
6	0.1	1.5626
6	0.6	1.5664
11	0.1	1.57
11	0.6	1.5738

4.1 The Simulation results of the 2D model

In this simulation, two voltages were applied on the electrodes to measure the capacitance at different values of pressure and humidity. Figure (4.1) shows the electrical potential of 2D sensor. The different color shows the voltage level from red (high voltage) 1v to the blue (low voltage) -1v, while in figure (4.2), The diaphragm is revealed to have a significant degree of pressure., around the Lead Zirconate Titanate (PZT-5H) martial. The deflection in the diaphragm is clearly visible in figure (4.2) due to the effect of increasing the pressure.

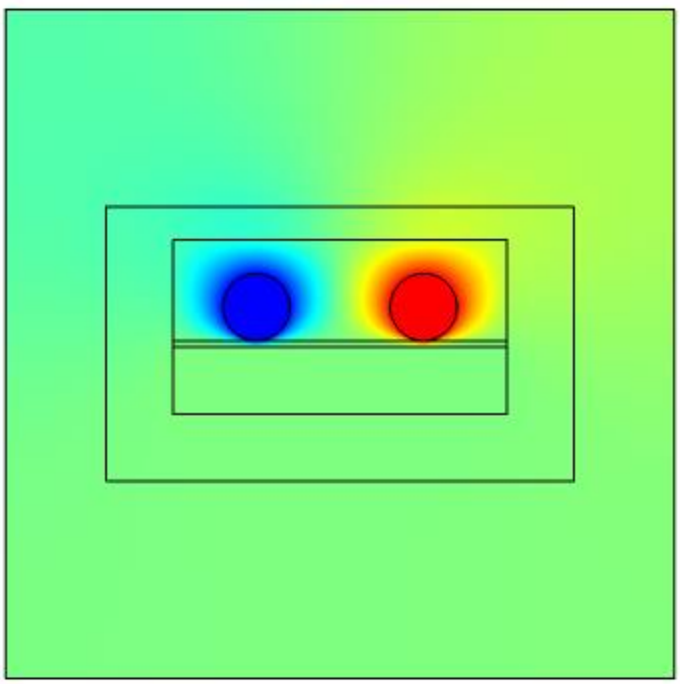


Figure (4.1): Electric potential

To verify the effectiveness of the 2D model, it is needed to compute the capacitance at different values of pressure and humidity. Therefore, the pressure value has been increased from 1 bar to 100 bar at different humidity to compute the change in the capacitance due to this effect.

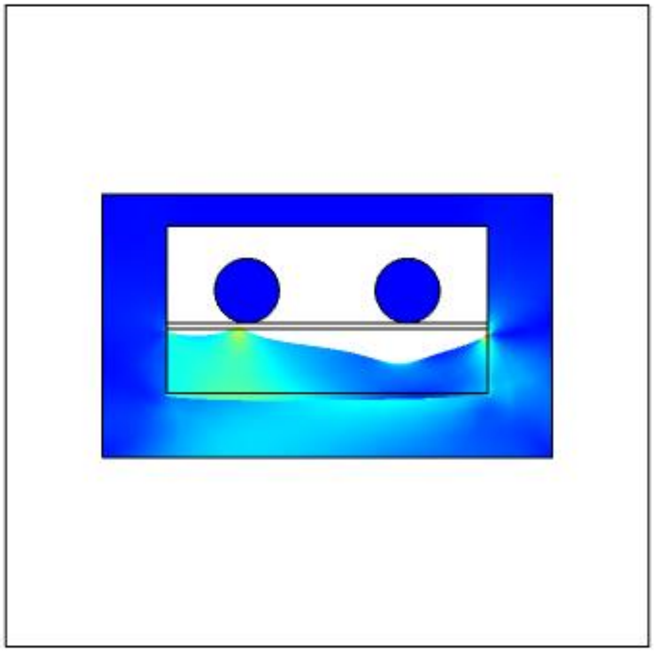


Fig (4.2): Pressure (N/m^2) of sensor

4.2 Maxwell capacitance results

The change in the data of the relative humidity, and pressure gave a varied Maxwell capacitance data that shown in the table (4.2). The values of the pressure were increased from 1 to 100 bar at different relative humidity values to study and evaluate the sensor sensitivity. From this data, it can be seen that the value of the capacitance has been increased from 157.11 picoFarad to around 173 picoFarad with increasing pressure. In addition, it has been noticed a change in the capacitance with increase the relative humidity. Figure (4.3) shown Maxwell capacitance results

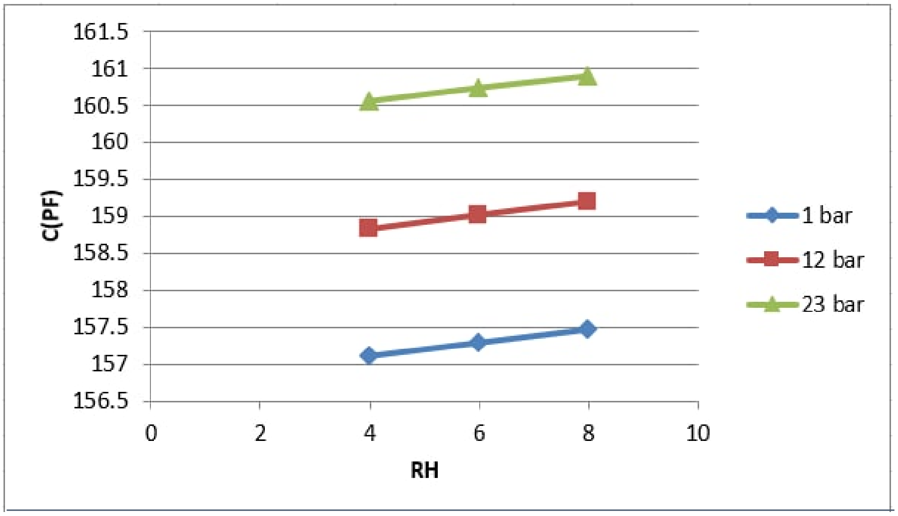


Figure (4.3): Maxwell Capacitance

Table (4.2) Maxwell Capacitance values

P0 (bar)	Hu	Maxwell capacitance (pF)
1.0000	0.40000	157.11
1.0000	0.60000	157.29
1.0000	0.80000	157.47
12.000	0.40000	158.83
12.000	0.60000	159.02
12.000	0.80000	159.20
23.000	0.40000	160.56
23.000	0.60000	160.74
23.000	0.80000	160.9
34.000	0.40000	162.28
34.000	0.60000	162.47
34.000	0.80000	162.66
45.000	0.40000	164.00
45.000	0.60000	164.19
45.000	0.80000	164.38
56.000	0.40000	165.73
56.000	0.60000	165.92
56.000	0.80000	166.11
67.000	0.40000	167.45
67.000	0.60000	167.64
67.000	0.80000	167.84
78.000	0.40000	169.17
78.000	0.60000	169.37

78.000	0.80000	169.57
89.000	0.40000	170.90
89.000	0.60000	171.10
89.000	0.80000	171.30
100.00	0.40000	172.62
100.00	0.60000	172.82
100.00	0.80000	173.02

To evaluate the senstivity of the multifunctional sensor, the change in the capacitance with increasing prussure is illsutrated in figure (4.4). This figure shows the simulated data for relationship between capacitance and pressure for the piezoelectric material at different values of humidity. It can be seen from the figure that the initial capacitance for the system is about 157 picoFarad. The capacitance varies from 157 to 173 picoFarad for the sensing film and the piezoelectric material. This graph reveals a suitable information about the effect of increasing pressure on the capacitance which is more dominant than increasing the relative humidity, and the sensor seems to be more sensitive to the change in the pressure.

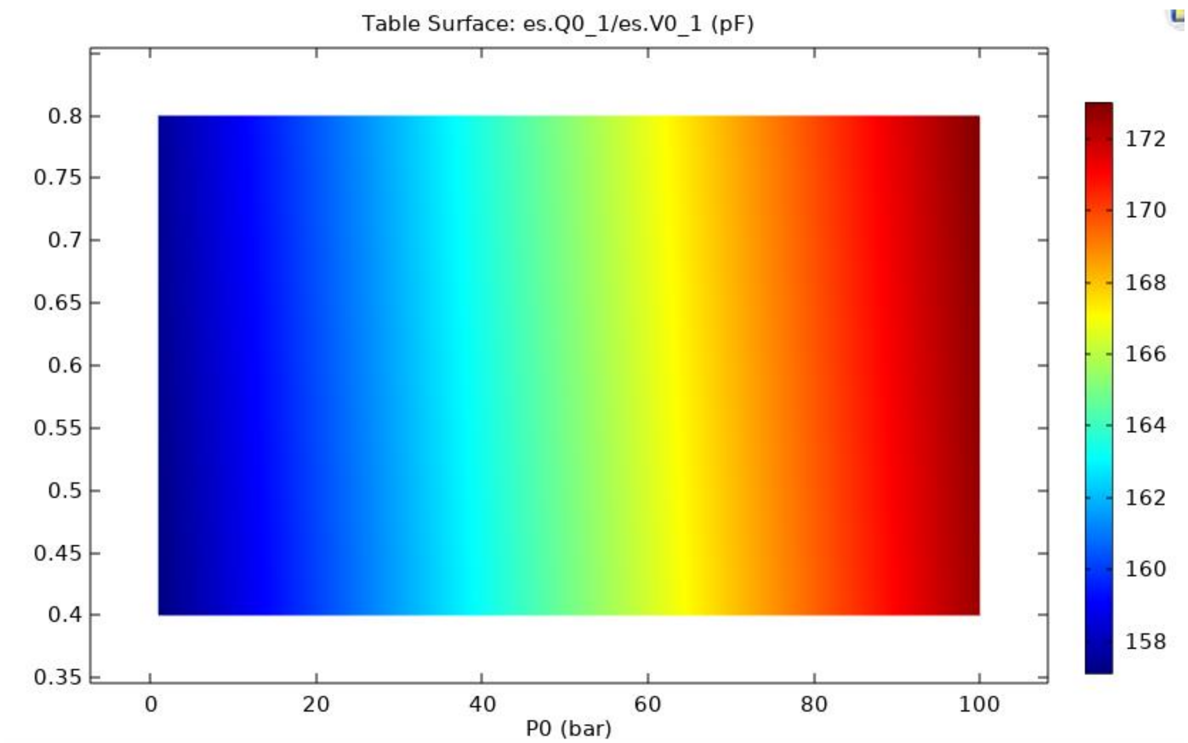


Figure (4. 4): Color surface view showing the change in the capacitance with changing pressure and humidity

4.3 The Simulation results of the 3D model

In the second simulation, a 3D model of the multifunctional sensor was constructed. The idea of this simulation is to develop a more accurate sensor and compering its work with the 2D model.

In this simulation, two voltages were applied on the 3D electrodes to measure the capacitance at different values of pressure and humidity. The pressure has been changed from 1 bar to 11 bar. At each pressure value, two relative humidity were assumed which are 0.1 and 0.6. Figure (4.5) shows the electrical potential of capacitive (humidity and pressure) sensor. The change in color shows the voltage level from red (high voltage) 1v to the blue (low voltage) -1v.

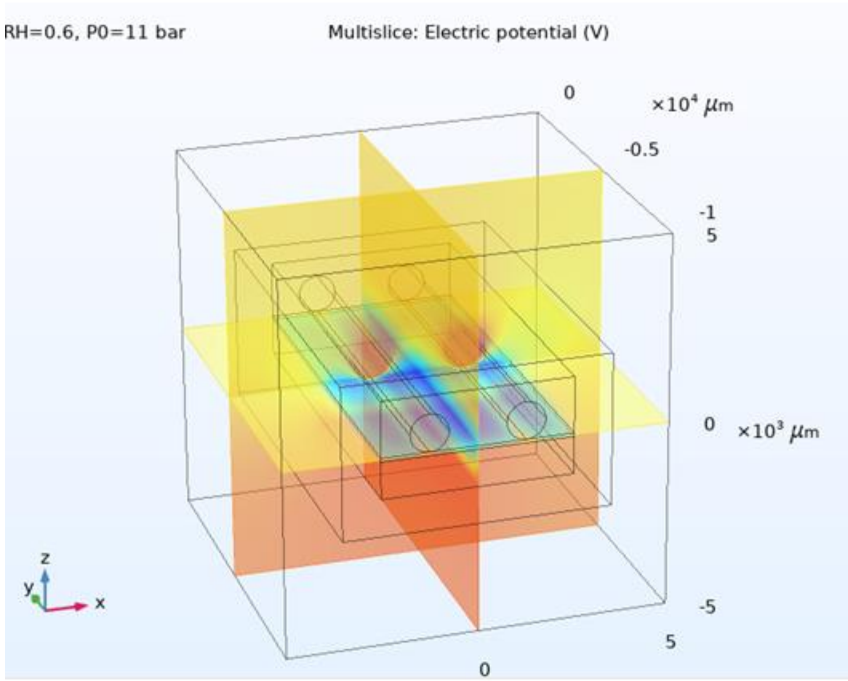


Figure (4.5): Electrical Potential for sensor (V)

Figure (4.5) is a multi-slice diagram which illustrates the electric potential distribution of the whole model where we can see the electrodes and the sensing film area.

In figure (4.6), the pressure distribution is shown where the highest level of applied pressure is at the diaphragm (reaches $20*10^5$ bar) because the poly silicon material has strong influence on the mechanical sensitivity, low stress compared to other materials.

The total stress on the sensor is also illustrated. It can be noted that the stress inside the sensor is bigger than the applied pressure due to small spaces presented by the sensing film. In addition, a clear deflection can be seen on the diaphragm due to the effect of increasing the applied pressure.

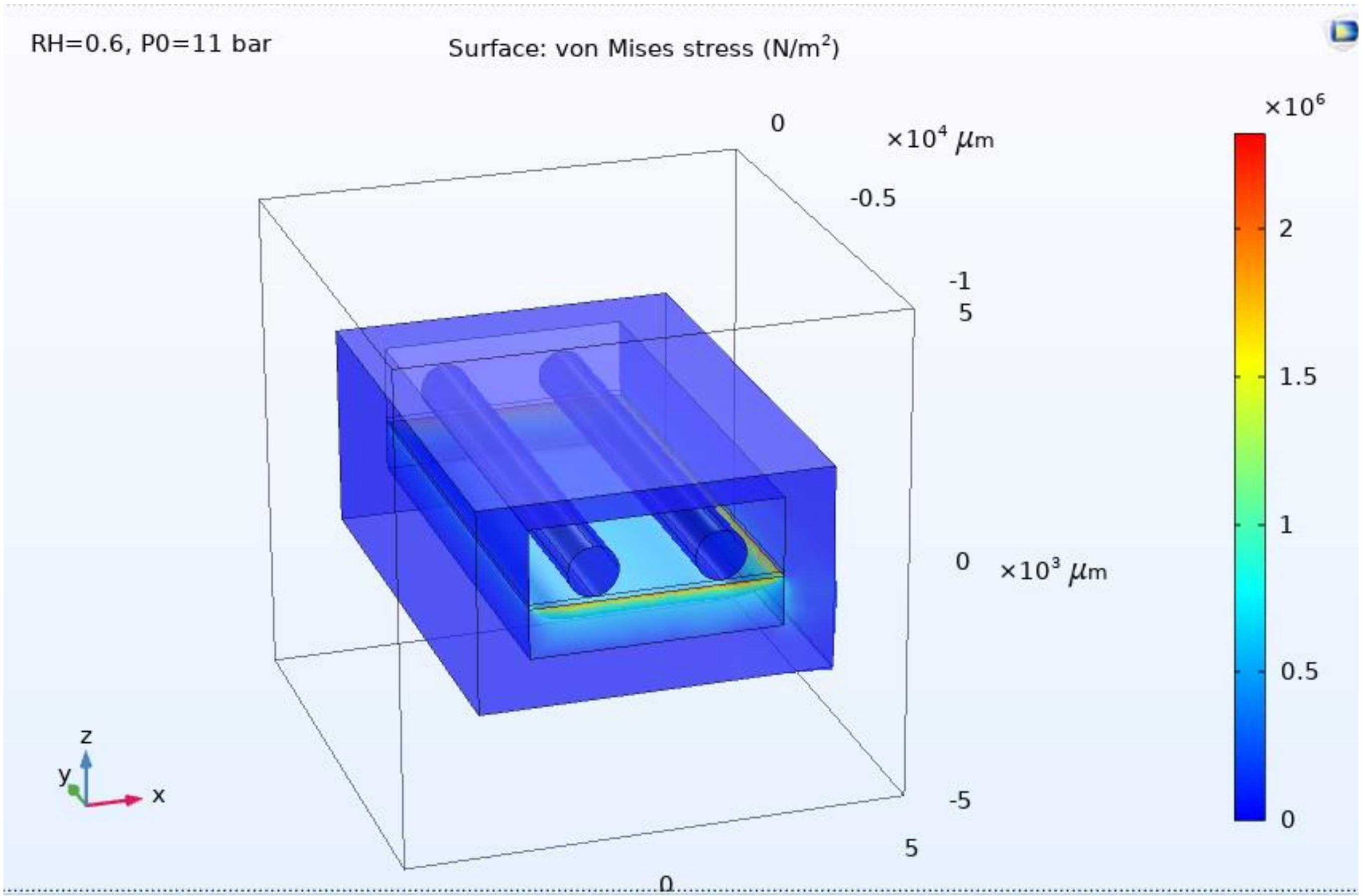


Fig (4.6): Pressure (N/m²) of sensor

The electric field distributed is shown in figure (4.7) where we can see the field through the voltage terminals from the inner toward to the outer silicon cage at time 0.6 s.

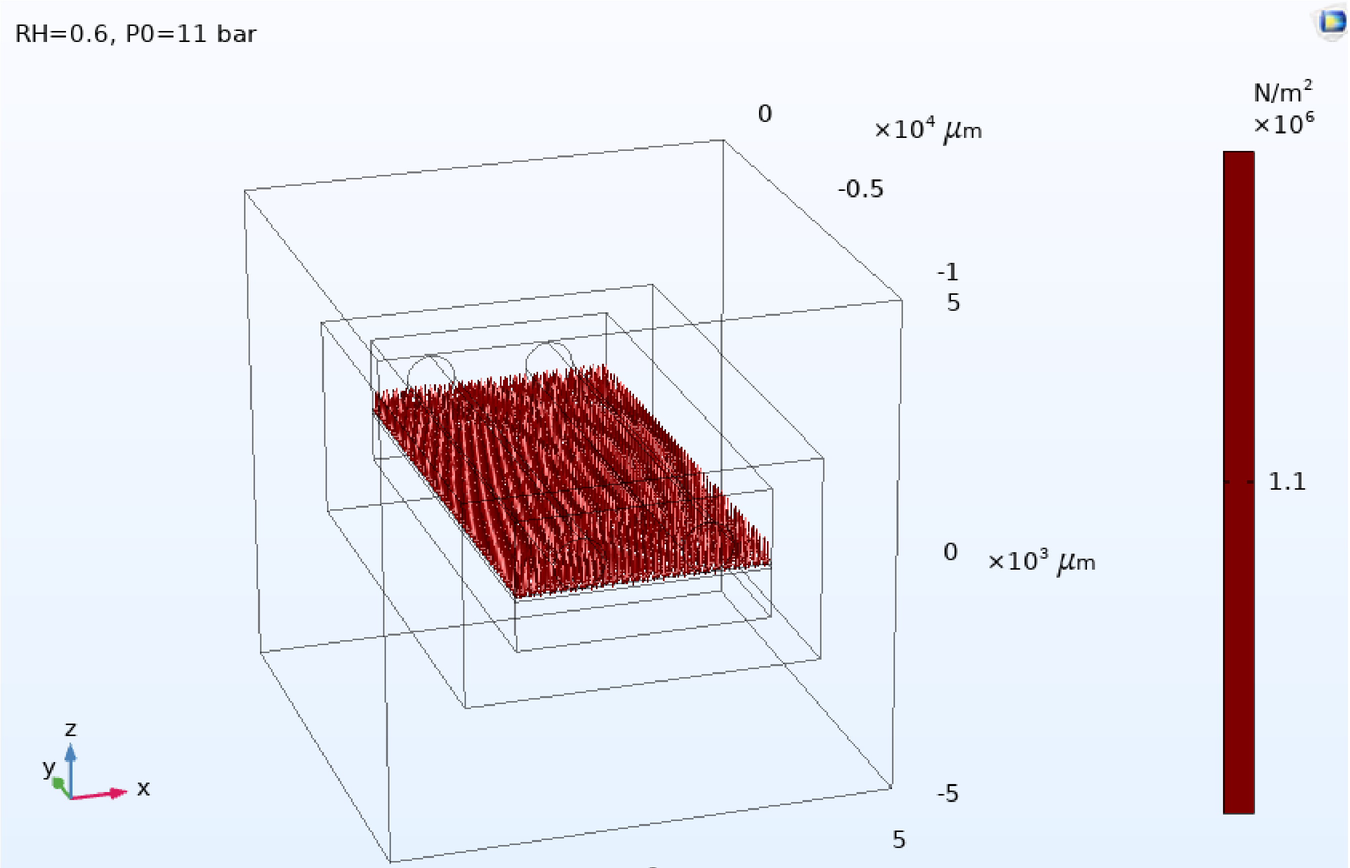


Figure (4.7): Total boundary load flux for model

4.4 Maxwell capacitance results

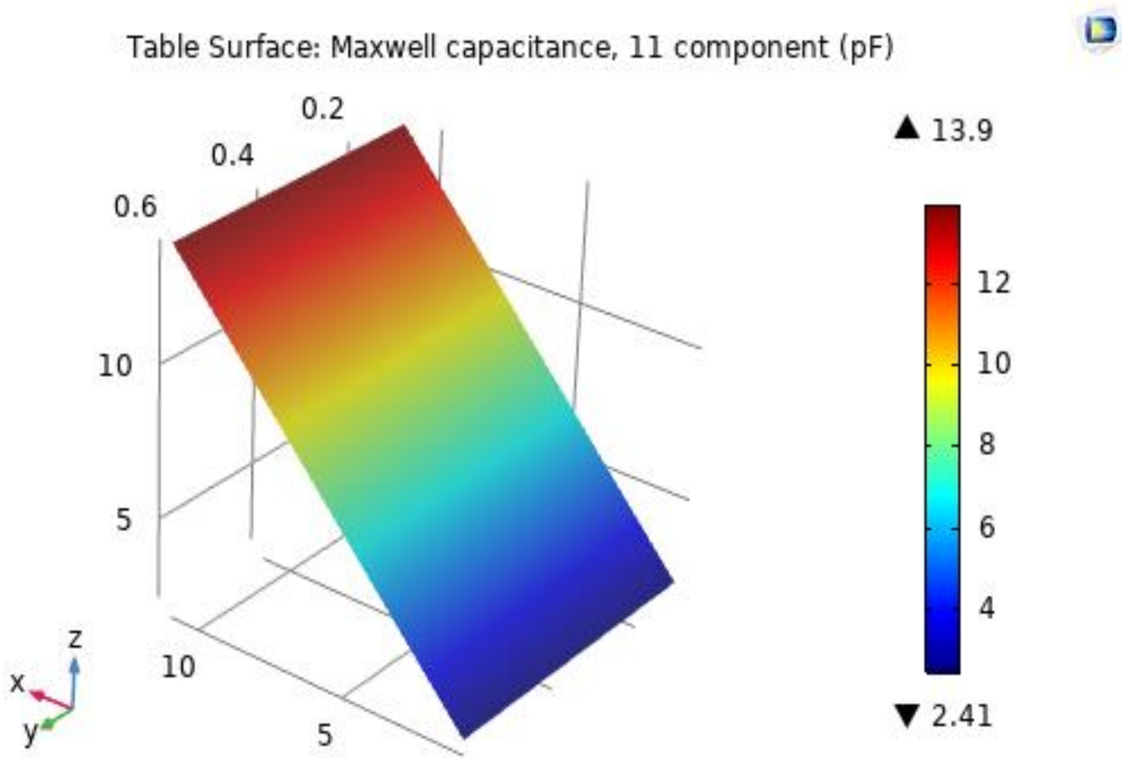
To verify the effectiveness of this model, it is needed to compute the capacitance at different values of pressure and humidity. Therefore, the pressure value has been increased from 1 bar to 11 bar at different humidity to compute the change in the capacitance due to this effect.

To calculate capacitance matrices.The computed data for the parameters (relative humidity and Pressure) gave a varied Maxwell capacitance data shown in the table (4.3).

Table (4.3) Maxwell capacitance data

P0 (bar)	RH	Maxwell capacitance, component (pF)
1.0000	0.10000	2.4119
1.0000	0.60000	2.4126
3.0000	0.10000	4.7165
3.0000	0.60000	4.7179
5.0000	0.10000	7.0210
5.0000	0.60000	7.0231
7.0000	0.10000	9.3256
7.0000	0.60000	9.3284
9.0000	0.10000	11.630
9.0000	0.60000	11.634
11.000	0.10000	13.935
11.000	0.60000	13.939

The maxwell capacitance has increased from 2.4 to around 14 pF with increasing the pressure from 1 to 11 bar. The change in the relative humidity from 0.1 to 0.6 has also effected the computed capacitance. The humidity and pressure sensitivity of the model response is presented in figure (4.8) Here, we can see how critical packaging considerations are for MEMS development..



Figure(4.8): Maxwell capacitance (pF)

Figure (4.8) shows a typical increase in the capacitance between the two terminals when the pressure increases with time for two fixed values of relative humidity. The solution and obtaining the computed Maxwell capacitance is by solving the simultaneous equations.

In details, the capacitance begins with 2.4119 pF at 1 bar pressure and a 0.1 relative humidity. A significant increase in the computed capacitance can be distinguished with increasing the pressure to 11 bar where the value of the capacitance reaches 13.939 pF. There is also an increase in the capacitance with increasing the relative humidity.

Electric potential is generated at the voltage terminal electrodes at the left and right of the silicon cage when the sensing film traps water molecules or the piezoelectric material detect any applied pressure which it disturbs the potential energy of the whole system which in turn influences the capacitance of the system. Figure (4.9) shows the distribution of pressure of fluid traveling from inner terminals 0.95 V at 0.9 s. The increase in electric potential in cylinders, causes increase in pressure and relative humidity.

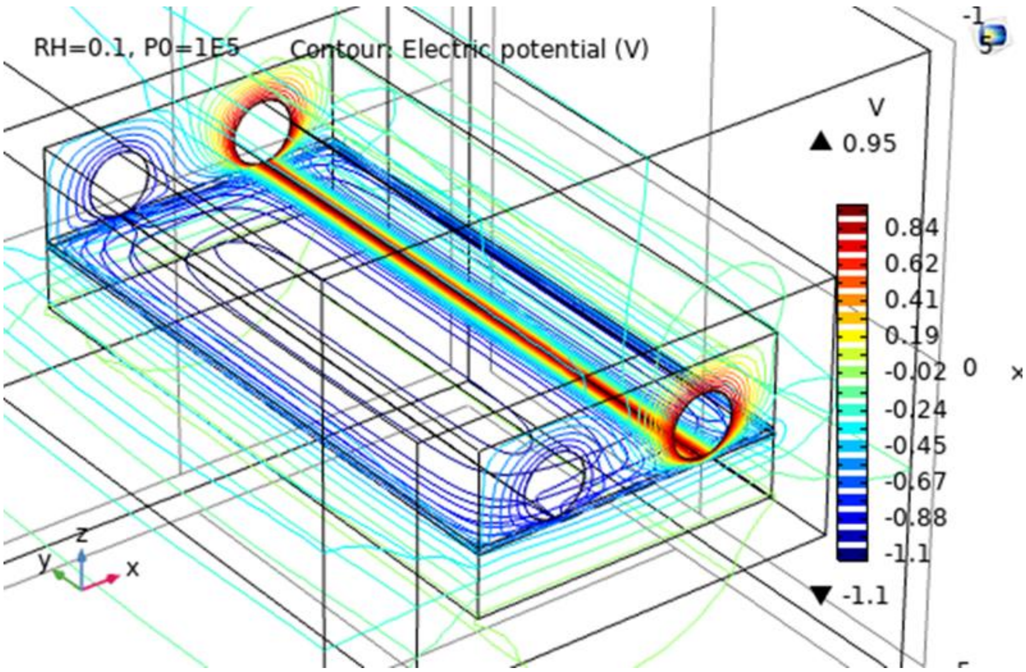


Figure (4.9): Contour of electric potential(V)

Compering the result of the 3D model with the 2D model , it can be noted that the increase in the computed capacitance with increasing the applied pressure for the 3D model is higher than the increase in the capacitance of the 2D model. The change in the capacitance is from 157 pF to 173 pF with increasing the pressure to 100 bar in the 2D model while it was from 2.4 pF to 13.9 pF in the 3D model with increasing the pressure to just 11 bar.

moreover, the change of the computed capacitance with changing the relative humidity from 0.1 to 0.6 has little effect compering with the pressure change.

4.5 Final results

The above results give the following sensitivities of the sensor:

$$S_P = \frac{\Delta C}{\Delta P} = 18.6 * 10^{-3}\ fF/bar$$

$$S_{Rh} = \frac{\Delta C}{\Delta Rh} = 0.372\ \ fF/bar$$

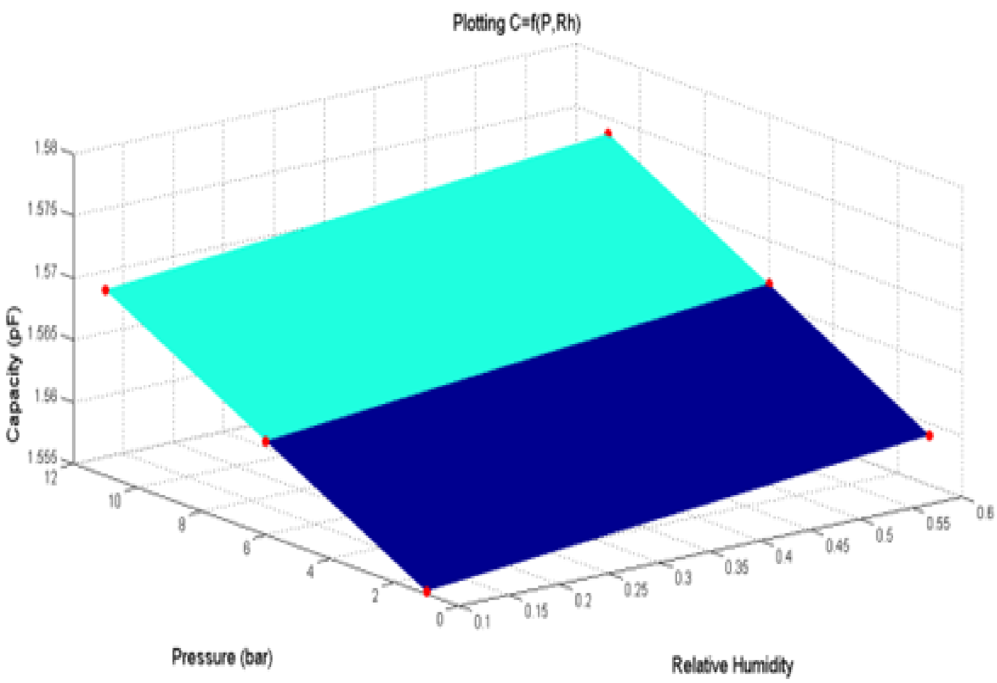


Figure (4.10): Plotting obtained results $C = f(p, RH)$, capacitance as function of pressure and relative humidity

Figure (4.10) illustrates the final results of the 3D model where the change in the capacitance in clear due to changing the pressure and relative humidity.

Chapter five
Conclusions

5.1 Conclusions

1. In this project, a multifunctional sensor has been proposed. The proposed senor was designed and simulated to work in a dual mode for different reasons and applications. The sensor has been used to measure the humidity and pressure as a function of capacitance where it has been designed and developed in COMSOL Multiphysics 5.5. The simulation was carried out for different values of applied pressure and relative humidity and two models have been designed (2 D and 3 D). The simulated results were obtained from COMSOL simulator is micro range.

2. The results have revealed a significant increase in the computed capacitance with increasing the applied pressure for the 3D model and was higher than the increase in the capacitance of the 2D model. The change in the capacitance is from 157 pF to 173 pF with increasing the pressure to 100 bar in the 2D model while it was from 2.4 pF to 13.9 pF in the 3D model with increasing the pressure to just 11 bar.

3. In terms of the relative humidity, the change of the computed capacitance with changing the relative humidity from 0.1 to 0.8 has little effect compering with pressure change.

5.2 Future research directions

1. Extending the work of the sensor to include more parameters in the measuring

range where multifunctional sensitive material can be used as a sensing film.

2. Trying to use this type of the sensor to monitor the health status of some MEMS applications
3. Design multifunctional sensor in the nano range for NEMS applications.

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