DESIGN AND MODELING OF RF MEMS SWITCH WITH FATIGUE RESISTANT OPERATION

DISSERTATION-II

Submitted in partial fulfillment of the requirement for the award of the Degree of

MASTER OF TECHNOLOGY
In
Manufacturing Engineering

By

(Sourabh Sikdar)

Under the Guidance of

Harpreet Singh
(Assistant Professor)

LOVELY PROFESSIONAL UNIVERSITY

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PHAGWARA (DISTT. KAPURTHALA), PUNJAB

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MAY 2015

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Lovely Professional University Jalandhar, Punjab

CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled **"DESIGN AND MODELING OF RF MEMS SWITCH WITH FATIGUE RESISTANT OPERATION"** in partial fulfillment of the requirement for the award of degree of **Master of Technology (Manufacturing Engineering)** and submitted in Department of Mechanical Engineering, Lovely Professional University, Punjab is an authentic record of my own work carried out during period of Dissertation under the supervision of **Mr. Harpreet Singh**, **Assistant Professor**, Department of Mechanical Engineering, Lovely Professional University, Punjab.

The matter presented in this dissertation has not been submitted by me anywhere for the award of any other degree or to any other institute.

Date:

(Sourabh Sikdar)
Reg. No. 11305393

This is to certify that the above statement made by the candidate is correct to best of my knowledge.

Date:

(Harpreet Singh)
Supervisor

The M- Tech Dissertation examination of Sourabh Sikdar, has been held on___________

Signature of Examiner

LOVELY PROFESSIONAL UNIVERSITY

PHAGWARA – 144402, PUNJAB

CANDIDATE DECLARATION

I, Sourabh Sikdar, Reg. No. 11305393 hereby declare that the work presented entitled "**DESIGN AND MODELING OF RF MEMS SWITCH WITH FATIGUE RESISTANT OPERATION**" in partial fulfillment of requirements for the award of Degree of Master of Technology (Manufacturing Technology) submitted to the Department of Mechanical Engineering at Lovely Professional University, Phagwara is an authentic record of my own work carried out during the period from JAN 2014 to MAY 2015, under the supervision of Mr. Harpreet Singh (Assistant Professor), Department of Mechanical Engineering. The matter presented in this thesis has not been submitted in any other University/ Institute for the award of Degree of Master of Technology. Furthermore, I also declare that I will not publish this work in any other Journals/ Conferences/ Workshop seminars except the one chosen by supervisor. The presented work is the property of Lovely Professional University, Phagwara. If I found violating any of the above conditions, University has right to cancel my degree.

Signature of Student   Date:

Place:

ABSTRACT

This paper reports on the design and modelling of a low-actuation voltage microelectromechanical systems (MEMS) switch for high-frequency applications. The mechanical design of low spring-constant four meanders beams is presented first, and then using these beams to demonstrate with measured actuation voltages of as low as 1- 5V. Also, the effective stress and actuation voltage required for fixed-fixed membranes is analyzed using finite element modeling. The thickness (t) 1μm, width (w) 100 μm, length (L) is 220 μm of membrane is used. MEMS capacitive switch is more durable due to low power consumption, high sensitivity, IC compatibility and free from temperature effects. Shunt capacitive switches are more suitable for higher frequencies (5–100 GHz). Well-designed shunt capacitive switch results in low insertion loss (-0.04 to -0.1 dB at 5–50 GHz) in the up-state position and acceptable isolation (more than -20 dB at 10–50 GHz) in the down-state position. There are many materials being used to made substrate but the purpose of study is to frame a noval design of switch by using the 1400Å thickness of dielectric (Al_2O_3) and simulate on software. After finding the results analysis, von Mises stress of membrane is determined $1.09 x 10^6$ N/m^2, and the pull in voltage range is 1-5V. Also, the time interval of 5μs the displacement of membrane is found 0.88μm capacitance of 8.5 pF. The contact force of the membrane is $1.09 x 10^4$ N/m^2. To overcome the fatigue resistance, BN(CA) grade is used as a subtrate because it provides the highly resistance to the moisture as well as the strength of base to hold the membrane. The proposed research work is a new approach to use Boron Nitride as a substrate in capacitive switch. The fatigue strength of the aluminium membrane is 131 MPa from the previous conceptual results and the final results declared from the proposed and present study that the stress produced during the working cycle is 1.09MPa which is feasible and validated. The cyclic loading of the membrane validates the contact force computed during simulation process is 0.109 Pa/μm in 5μs, which is within the limits of acceptance. The simulation test is performed on Multi-User MEMS Process (MUMPS), Parellel Direct Solver (PARDISO) and Numerical simulations on COMSOL 5.0 which are numerically computed and validated.

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Nothing can be accomplished without an optimum compounding of divine guidance and perspiration, the real spirit of accomplishing a goal is through the way of excellence and field of study. I would have never came after completing my task without the cooperation boost and help provided to me by various personalities.

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I wish to place on record my gratitude for all those who have been enforcing on my work to this stage. I do not find enough words with which I can express my feeling of thanks to all my friends for their help, divine guidance and moral support which went a long way in the completing of my thesis.

Above all I had over my gratitude to the ALMIGHTY who bestowed me self- confidence, ability and strength to complete this work, I also thanks to my parents for their support and boost.

SOURABH SIKDAR
(Reg. No. 11305393)

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NOMENCLATURE

CPW	Coplanar Waveguide
DNA	Deoxyribonucleic Acid
LCD	Liquid-Crystal Display
LM	Liquid Metal
MEMS	Microelectromechanical System
RF	Radio Frequency
Al	Aluminium
Au	Gold
Cu	Copper
dB	Decibels
GaAr	Gallium Arsenide
GHz	GIGA Hertz
mW	Micro Watt
nH	Nano Hertz
Ni	Nickel
nJ	Nano Joule
Rh	Ruthenium
Ru	Rubidium
V	Voltage
ω	Angular Velocity
Ω	Ohm
$	Dollar
°	Degree
µ	Micro
µm	Micrometer
µs	Micro Seconds
Å	Angstrom

CONTENTS

CHAPTER-1: INTRODUCTION

1.1 MEMS SYSTEM

(MEMS) Microelectromechanical Systems are operation technology used to create a small device or system that combines mechanical and electrical components that are constructed by batch processing techniques and can have in size from a millimeter or micrometers, these systems is to feel, incite and manipulate on the micro scale and get the effects on the macroscopic level. Adams and Layton (2002) described The MEMS applies design, engineering and manufacturing expertise of a board and various ranges of technical areas including integrated circuits, optics, fabrication technique, chemical engineering, and chemistry as well as materials science, instrumentation, packaging and fluid engineering. The MEMS is also found at the wide range of markets and applications that contain MEMS devices. MEMS can also found in systems ranging across medical, automotive, electronics, defense and communication applications. Ruf, H. H. et al. (2010) also described the MEMS device is used in bio-sensors, computer disk, inkjet printer heads, projection display chips, drive read/write heads, micro valves, airbag sensors, , optical switches, blood pressure sensor and many products that are all manufactured and shipped in high commercial volumes. MEMS have identified as one of the most hopeful technologies for the 21st century have the potential to revolutionize both industries and consumer products by combining silicon based microelectronics with micromachining technology. Microsystem and its technique based devices have the potential to dramatically effect on all of our lives and the way we live. If micro fabrication had seen to be First micro manufacturing revolution, MEMS are the second revolution. Robertson et al. (2004) described the design and fabrication of RF MEMS, This Chapter introduces the field of MEMS Componet and their features. Firstly prefaced to MEMS, its diachronic current, definitions and potential applications or gives the state of the MEMS market concerning mini acturizations, ,Second part inspections are rove of MEMS actuators and sensors, the phenomena that can be pictured upon with MEMS devices and an abbreviated description of the basic actuation and sensing mechanisms. The final part instances the challenges facing the MEMS industry for the commercialization and success of MEMS. Micro-Electro-Mechanical Systems, or MEMS is a technology determined as mini acturized mechanical and electromechanical element that can be made by the techniques of micro fabrication The vital strong-arm dimensions of MEMS devices can vary from well below1 micron on the lower end of the dimensional spectrum, like the type of MEMS devices vary from relatively simple structure having no moving element, extremely complex electromechanical system with multiple moving element under the control of integrated microelectronics. The criterion by MEMS is at least some element having some sort of mechanical functionality whether its element cannot move. The term used to determine MEMS varies in different parts of the world. In the United States they are mostly called MEMS, also spell in about other voices of the world they are “Microsystem Technology” or “micro machined devices”.

1.2 COMPONENT OF MEMS

The operational ingredients of MEMS are mini acturized structure, sensors, actuators and microelectronics, the most illustrious element are the Mini sensor and mini actuators. Mini actuators and Mini sensor are further categorized as “transducers”, which are change energy from one form to another. In case of Mini sensor, the device change a calculated mechanical signal into an electrical signal (Adams and Layton, 2002).

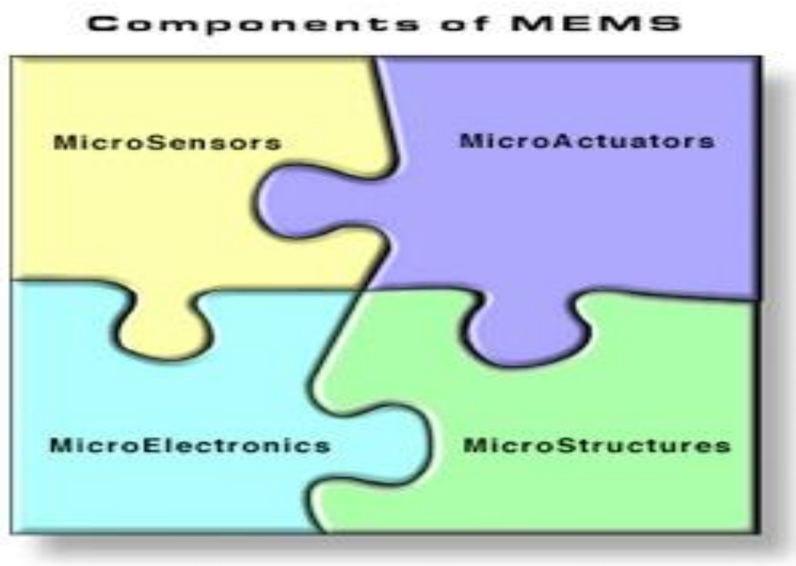


Figure 1.1: Component of MEMS

Likely MEMS starts to be satisfied when these small sensors, small actuators, and small structures can all mixed into a common silicon substrate along with IC, spell the electronics are manufactured using ‘IC’ procedure sequences, the micro mechanical system component is manufactured using “micro-machining" processes that scratch away parts of the silicon wafer or add new morphologies layers to form the mechanical and electromechanical devices. It’s more interesting if MEMS can be mixed with microelectronics and other technologies such as nanotechnology

(i) Transducer

A transducer translates one form of data, energy or signal into another form. The transducer is used to admit both term actuators and sensor is the nearly generically and widely used in MEMS.

(ii) Sensor

A sensor evaluates data from a besieging environment and gives an electrical output signal in response to the parametric quantity it calculated. These energy fields include: velocity; force; position; acceleration and pressure on mechanical.

(a) Heat flow, entropy, temperature on thermal.

(b) Concentration, reaction, composition on Chemical.

(c)Wave intensity, wavelength, polarization reflection, phase, refractive index on Radient

(d) Field intensity, permeability, magnetic moment flux density on magnetic.

(e) Capacitance, resistance, voltage, current, polarization, charge on Electrical.

(iii) Actuator

An actuator changes an electrical signal into a gesture. It can make a force which controls other mechanical devices or the surrounding environment perimeter to do some useful work

1.3 HISTORY OF MEMS

The following list summarizes some of the key MEMS milestones (Adams and Layton, 2002)

- 1950's

1958 First silicon strain gauges available on site.

1959 Richard Feynman gives a milestone presentation at California Institute of Technology- "There's Plenty of Room at the Bottom" - also challenge by offering 1000 to the first person to create an electrical motor smaller than 1/64th of an inch

- 1960's

1961 First silicon pressure sensor is manifested.

1967 Surface micromachining concept is revealed Westinghouse creates the Resonant Gate Field Effect Transistor and gives the description of sacrificial material to free micro mechanical devices from the silicon substrate.

- 1970's

1970 First silicon accelerometer is manifested.

1979 First micro machined inkjet nozzle manifested.

- 1980’s

1980 First experiment is conducted on surface micro machined silicon.

Also 1980’s micromachining leverages microelectronics industry and widespread experimentation and documentation increase public interest.

1982 Make a Disposable blood pressure transducer.

1982 First LIGA Process is held on fabrication.

1988 First MEMS conference organizers.

- 1990's

Methods of micro machining pointed to amending of sensors.

1992 First micro machined hinge manufactured.

1993 First micro machined accelerometer traded (Analog, ADXL50, Devices).

1994 the first deep reactive Ion etching is patented.

1995 First Bio-MEMS created.

1.4 ADVANTAGES OF RF MEMS

Kumar and Fletcher (2014) framed RF-MEMS switches are the micro mechanical switches which are designed to operate at RF at mm-wave frequencies (0.1 to 100 GHz). The advantages of MEMS switches over FET switches or PIN diode are:

(i) Near-Zero Power Consumption

Electrostatic actuation requires 30-80 V but does not consume any current, leading to very low power dissipation (10-100 nJ per switching cycles). Thermal/ magnetic switches consume a lot of current unless they are made to latch in the down-state position once actuated (Choi and Lee, 2006).

(ii) Very High Isolation

RF-MEMS metal-contact switches are fabricated with air gaps, and therefore they have very low off-state capacitances (2-4 fF) resulting in excellent isolation at 0.1-60GHz. Also, Lee and Yong (2010) mentioned capacitive switches have a capacitance ratio of 60-160 which provide excellent isolation from 8-100GHz.

(iii) Very Low Insertion Los

RF-MEMS capacitive switches and metal-contact have an insertion loss of 0.1dB up to 100GHz.

(iv) Linearity and Intermodulation Product

MEMS switches are awfully linear devices, hence in very low Intermodulation products in g atuning and switching operations. Grant and Denhoff (2004) showed their performance is 30-50 dB improved than PIN or FET switches.

(v) Low Cost

RF MEMS switches are fabricated using surface micromachining techniques and can be built on Pyrex, quartz, LTCC mechanical grade high-resistivity GaAs or silicon substrates.

(vi) Relatively High Speeds

The switching speed of the most electrostatic MEMS switches is 2-40 μs,

1.5 LIMITATIONS OF RF MEMS SWITCHES

There are following limitations of RF MEMS switches,

(i) Device Packaging

RF MEMS switch carrying is essential not only for the proper device operation, but also for the fast dispersion of the technology. Yadav et al.(2011) described The functional features of the devices are severely touched by the presence of water vapors, oxygen, hydrocarbons and other contaminants.

(ii) Power Handling and Reliability

The number of one-off cycles of a MEMS device is looked at to be one of the major dependability criteria (Adams and Flecther, 2002). The devices have been described with life time up to a few billion cycles, under low power disciplines (0.5-5mW). The bankruptcy mechanisms depend on the RF Power used and can be due to thermal stress, dielectric break down, self-actuation or critical current density issues. Dielectric charging, pitting, hardening, dielectric constitution typically sabotages the dependability of the devices. Talking about dependability issues in detail, we have five examples for Ohmic and capacitive switches.

(iii) Contamination

The impedance increases due to organic deposits, absorbed hydrocarbon layers and contamination around the contact area and can be avoided by proper material selection

(iv) Stiction

It arises when the surface interaction energy at a contact point is greater than the restoring force which is given to bring the switch in the equilibrium/open position. Zyao (2003) described In such an instance the RF MEMS switch will stick in the closed position. At high current disciplines, a section will generally be gathered by hot-welding.

(v) Wear

The tendency may be damaged by a big effect force which can be much greater than the high static contact force required for low contact resistance.

(vi) Dielectric charging

The hypothesis of dielectric charging affects the concept of charges tunneling into the dielectric and becoming tired. In an effort to maximize the on-capacitance of a MEMS capacitive switch, the dielectric is typically made rather thin, normally less than 3000 A

1.6 APPLICATIONS OF MEMS

Adams and Layton (2002) mentioned the applications of MEMS in various diversified fields of engineering, medical and operations and industries are as follows:

1.6.1 MEMS on Automotive Airbag Sensor

The automotive air bag sensor is one of the first commercial- grade devices using MEMS. They are in far-flung use today in the form of a single chip holding in a smart sensor. The accelerometer is basically a capacitive or piezo-resistive device consisting of a suspended pendulum proof mass/plate assembly. As acceleration acts on the proof mass, micro machined capacitive or piezo-resistive plates sense a change in acceleration from deflection of the plates.

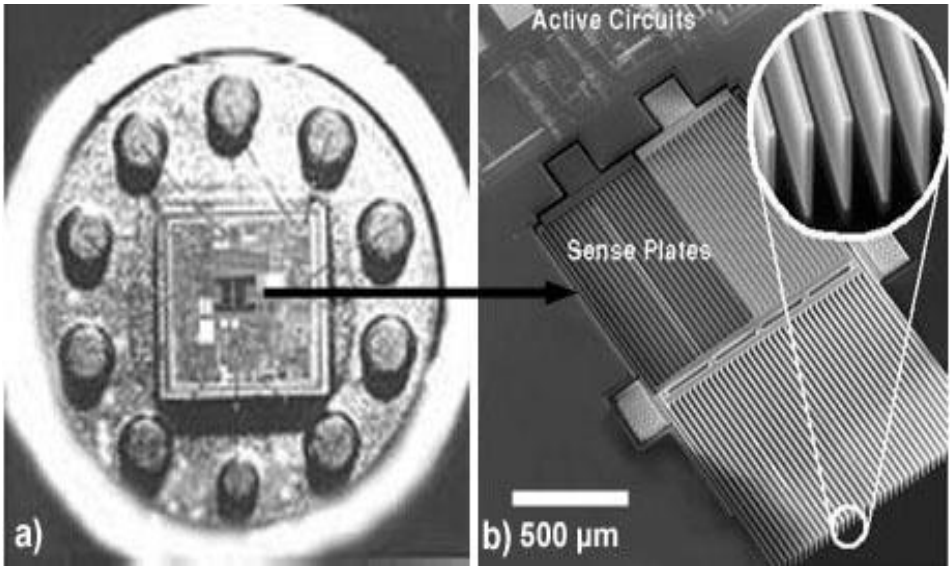


Figure 1.2: MEMS Device as Car Bag Sensors Depiction

1.6.2 MEMS on Medical Pressure Sensor

Some other example of an exceedingly successful MEMS application pressure sensor used to monitor blood pressure in the hospital. The sensor plug into a patient's intravenous line and monitor the blood pressure sensor that cost much more than expected, these expensive devices measure blood pressure with a small tube and diaphragm arrangement that to be connected to an artery with a needle.

1.6.3 MEMS Overhead Display (Projection)

Adams and Layton (2002) described ahead of time MEMS devices used for a diversity of display application is the digital micro mirror device the device contains tiny pixel each measure 16x16 u and capable of rotating by 10. MEMS enabled the micro mirror to be only 1 µm aside, ensuring in an image taking up a larger 90 percentage of space on the digital micro mirror chip as compared to a typical LCD which has only 12-15% this shortens pixelation and develop a sharper and brighter image.

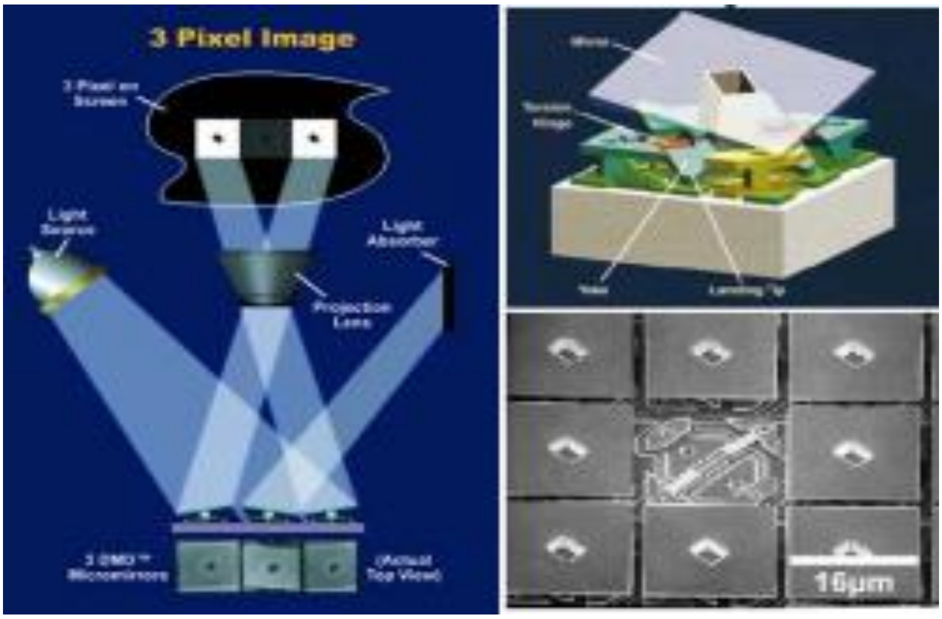


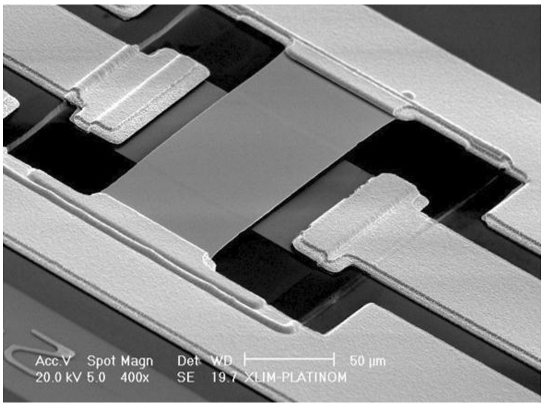
Figure 1.3: Projector Display of LED Microscopic View

1.6.4 Bio-MEMS

Fior et al. (2011) decribed Over the past few decades, some extremely advanced product has come forth from bio MEMS companies that support major social issue such as DNA sequencing, water, discovery drug and environmental inspection. It focuses on micro fluid system as well as chemical testing and processing, but many devices are still under development, micro fluidic system typically contains silicon micro machined system but with the help of MEMS it is easier on medial field.

1.6.5 On Radio Frequency MEMS

RF MEMS is one of the quickest developing areas in commercial MEMS technology, because its higher accuracy over FET and diodes very high isolation and performance on a common switch is shown below.



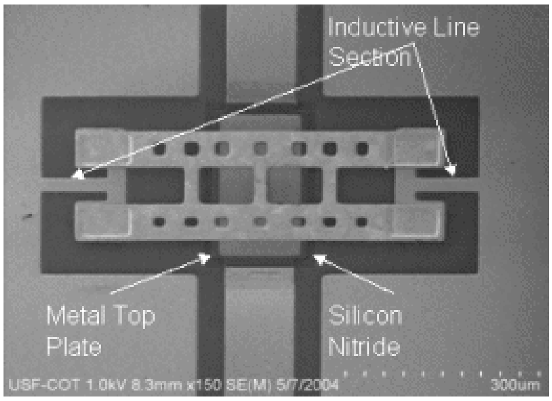


Figure 1.4: Capacitive Shunt and Shunt in Series Arrangement of RF MEMS

1.7 AIM OF WORK

(i) To make a Novel RF-MEMS switch that can transfer Radio frequency wave through it, also the analysis, fatigue resistance operation, basically it is making capacitive shunt switches mounted on Coplanar Waveguide (CPW). The need of shunt capacitive switches be fitted for frequency of (3-100 GHz). A good designed shunt capacitive switch gives low insertion loss up to (0. 04 -0. 1 dB) at (5-50 GHz) in the upstate position and also the isolation of (more than 20 dB at (11–51 GHz) in the down state position will trying to achieve this in our design.

(ii) Maximum approach to removal of sharp edges to device for less stress concentration, Because many of switches having a sharp curve edges so that stress concentration is more between two adjacent faces and will try to resolve it by using curves or bevel edges.

(iii) To make a non-conductive coating on the stiff membrane to cover the conductive material, now a days main factor of any electronic device is to resist the moisture and fatigue so that it can make the coating on the MEMS Bridge (stiff membrane).

(iv) To apply COMSOL 5.0 Multiphysics and CATIAV5 Softwares for simulation of RF MEMS Design. Analysis is done by COMSOL and designing is done on CATIA V5.

CHAPTER-2: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews previous work on MEMS which is done by researchers. It is important to understand how MEMS/NEMS and RF MEMS has been previously used. In this chapter, several research examples of MEMS/NEMS are given in order to demonstrate the process of their design, modeling, simulation and fabrication, as these are used in different scenarios and the related surveyed literature is presented in the following paragraphs.

2.2 LITERATURE REVIEW

Bhushan (2003) presented a very important review regarding causes of stiction and adhesion, along with methods to reduce the stiction and different measurement techniques in commercial ME Sand magnetic storage devices. Several techniques for adhesion measurement, i.e., surface force apparatus, atomic force microscopy (AFM), micro-triboapparatus, and cantilever beam array, were addressed. Adhesion between solids arises from the interatomic forces exerted across the interface. These forces may be strictly surface forces in the sense that they derive from the surface atoms themselves. Valence bonds provide surface forces. Surface charges also provide surface forces; these occur when ionic surfaces are in contact with other ionic solids. They will also occur if an electrically charged layer is formed at the interface, e.g., during sliding ~the triboelectric effect! Metallic bonds can form primarily in metal–metal pairs. All solids will, in addition, experience adhesion due to van der Waals interactions between atoms below the surface layers. Hydrogen bonds can occur in polymers. Adhesion interactions may often be calculated in terms of free surface energies. The energy required to create new surface, ex- pressed over an area consisting of many atoms in the surface lattice, is referred to as the free surface energy. The higher the surface energy of a solid surface, the stronger the bonds it will form with a mating material. One obvious suggestion is to select materials that have a low surface energy. The use of lubricants at the interface reduces the surface energy. Ma- terials with low work of adhesion result in low adhesion, where work of adhesion represents the energy that must be applied to separate a unit area of the interface or to create new surfaces.

Yapu (2003) presented a survey on stiction and hostile to stiction research for MEMS gadgets. A few test perceptions of stiction in micro-machined accelerometers and RFMEMS switches were exhibited, and some criteria for stiction of micro- and Nano-structures in MEMS and coming about because of surface powers were examined. The effects of surface harshness and natural conditions on stiction wonder and strategies to diminish stiction in MEMS and were inspected also. The extremely high surface-to-volume ratio of MEMS makes interface stiction, friction and wear significant factors in determining device reliability. These important problems must be solved in a near future for production of reliable and long lasting MEMS. Some criteria for stiction of microstructures with substrate have been reviewed in this paper. Though some physical models have been established, great efforts including experiments, molecular dynamics (MD) simulation and theoretical analysis are still needed to better understand the mechanisms of stiction, jump-in-contact (JC) and jump-out- of-contact, and adhesion hysteresis.

Zhao (2003) described some new experimental observation on stiction occur in RF-MEMS switch gives some criteria for stiction of micro structures in MEMS and NEMS due to surface forces (such as electrostatic, capillary, Casimir forces, van der Waals etc.) are also described. And also addressed as moisture, humidity factor, and the SAM (self-assembled monolayers) the prevent stiction effectively.

Robertson and Hudson (2004) addressed the modeling of electrostatically-actuated, capacitive switches are reviewed and fabrication steps are described. A lumped element model is used in order to facilitate the use of MEMS switches in electrical circuits. Finite Element Modeling showing forces created by the voltage across the switch is also presented. Fabrication steps are described. RF MEMS switches offer significant benefits and may be incorporated into many communication devices. Understanding switching behavior and characteristics are important for designers. It is concluded RF MEMS switches offer significant benefits and may be incorporated into many communication devices. Understanding switching behavior and characteristics are important for designers. Basic switch modeling has been completed and switches have been fabricated. Additional design work is required to account for impedance matching and other RF issues.

Zhu (2004) proposed a study that because of some application prerequisites and the gadget bundling, there is a critical requirement for comprehension the effect of RF MEMS switch outline on its execution as a capacity of temperature. High temperatures may cause clasping of the switch structure, which would prompt gadget disappointment. By difference, low temperatures may bring about an undesirably high draw in voltage that can trade off the gadget life by charge assemble up or lead to other disappointment modes. This article tends to this issue by examining demonstrating and experimentation approaches and, specifically, by breaking down a promising anxiety unwinding structure in light of film folding. Due to some application requirements and the device packaging, there is an important need for understanding the impact of RF MEMS switch design on its performance as a function of temperature. High temperatures may cause buckling of the switch structure, which would lead to device failure. By contrast, low temperatures may result in an undesirably high pull-in voltage that can compromise the device life by charge build-up or lead to other failure modes.

Bails and Martinez (2005) demonstrated the mixed signal multi domain simulation tool Chatoyant, to model and simulate an RF MEMS shunt switch. It also verifies his analysis and simulation over these commercial tools likes Ansys and CoventorWare, so that it would give better results through these commercial tools,also gives a hierarchal approach in modeling of RF MEMS shunt switches taking a good illustration of chatoyant's and also shows the advantage of the hierarchal modeling technique and concluded the unique possibilities of a system tool based on a modular hierarchal approach.

Hass et al. (2005) introduced the principle of MEMS voltage step-up converter, his voltage converter withstands potential benefit so that it can hinge on process integration and mini acturization. The electrical property of voltage convertor had analyzed thru the charge pump and SIMILINK modal library also give a design approach to fabricate a prototype of MEMS devices.

Bhushan et al. (2006) presented a comparative study for the Nano scale friction and adhesive properties of various SAMs with different hydrocarbon backbone chains (DP, ODP) and fluorocarbon backbone chains (PFDP) deposited via chemisorption onto an Al substrate. The influence of environment (RH and temperature), sliding velocity, and wear was studied, and the corresponding friction mechanisms were discussed. Both fluorocarbon and hydrocarbon SAMs showed a reduction in adhesive force, friction force, and coefficient of friction as compared to bare Al. PFDP, which has the lowest surface energy, also exhibited a lower adhesive force than either of the hydrocarbon SAMs. At small normal loads, the friction force for fluorocarbon was lower than for hydrocarbon SAMs. However, for high loads, the friction force was higher for fluorocarbon compared to hydrocarbon SAMs. The SAMs deposited on the Al substrate showed a negligible dependence of adhesive force on the RH. However, there was some decrease in coefficient of friction. This effect could be attributed to lubrication by the adsorbed water layer. The adhesive force for SAMs with a hydrocarbon backbone chain showed a temperature dependence. The adhesive force for SAMs with a fluorocarbon backbone chain, on the other hand, was temperature independent over the temperature range studied. The friction force for the SAMs on Al also showed little dependence on the sliding velocity. The SAMs with a fluorocarbon backbone chain showed much larger friction force, as well as, a larger sliding velocity dependence. Wear behavior of the SAMs is mostly determined by the molecule–substrate bond strengths. The long hydrocarbon chain molecules of ODP and the fluorocarbon backbone chains of PFDP showed higher critical loads than DP with its short hydrocarbon chain molecules and bare Al. From a tribological point of view, it is found that SAMs with compliant and long hydrocarbon backbone chains and those with fluorocarbon backbone chains show a highly desirable behavior. This study is expected to aid in the design and selection of appropriate lubricants for MOEMS/NOEMS on aluminum substrates.

Bhushan (2007) presented a critical review on mechanisms of adhesion and stiction, along with different measurement techniques and methods to reduce the stiction in commercial MEMS/NEMS and magnetic storage devices. Several techniques for adhesion measurement, i.e., surface force apparatus, atomic force microscopy (AFM), micro-triboapparatus, and cantilever beam array.

Chen (2007) framed a new type of wideband liquid RF MEMS reflective and absorptive switches. Taking different liquids such as galistan, mercury, ultra pure and ionic water. Briefly study the performance of liquid-metal switches made from galistan and mercury, such type of switch give excellent off state insertion loss less than 1.4dB up to 101 GHz, absorptive types give high power application and also effective in wideband having the range of 10-40 GHz at an insertion loss of 1.3 dB, off state loss 10dB, on state isolation of 40GHz.

Grenier et al. (2007) used germanium as a resistive material to make RF MEMS device and successfully demonstrated a device having SiGe transistor into a serial RF MEMS variable capacitor or switches without any RF loss. It also suggests that germanium has a good advantages compared to other materials for taking resistive materials.

Sen and Kim (2009) proposed a study of switch based on Liquid-metal droplet which is mostly on the low and slow application because of its large switching gap, lack of high speed actuation to overcome the problem used solid LM gas triple contact in place of entire droplet, the diameter of the droplet is 600μm for switching gap of 10μm.they made a switch having 60μm switching time and 5μm signal fall/rise.

Broue et al. (2010) studied a comprehensive behavior of low to medium levels of current and contact resistance having a pair of soft materials (Au/Au) mixed materials (Au/Ni, Au/Ru) and harder materials (Rh/Rh, Ru/Ru) and concluded that Au/Ru and AU/Au have better performance and better power handling capability.

Ferreria et al. (2011) reviewed the general scope of modeling and control of MEMS/NEMS researcher give the information about the various modeling and control technique which can help to find better and faster hardware computing software for designing aspect.

Yadav et al. (2011) provided a brief description of RF MEMS manufacturing technology advantages as well as application area also describe capacitive switches, advantages and application RF- MEMS fabrication technology and performance of capacitive switches.

Banitorfian et al. (2013) recommended a continuously-variable MEMS solenoid inductor operating up to 20 GHz. In this novel idea, a channel is provided to bypass the turns by injection of a conductive liquid (Galinstan). Corresponding to the level of ingestion, the reduction in the number of the turns varies the inductance value. The proposed Solenoid inductor is simulated with HFSS in Silicon substrate with Copper-type coil and injected conductive liquid. The EM simulation results show a maximum quality factor of 20 at 14 GHz and a tuning ratio of 1:5 at 16 GHz frequency. The minimum and maximum inductance values are 0.63 and 3.16 nH at 16 GHz, which demonstrates a tuning range equal to 400%. A novel liquid-based switched-turn variable inductor was proposed and simulated in HFSS. The variable inductor benefits of a continuous tuning state. A tuning range of 0.63−3.16nH was achieved at 16 GHz with a maximum quality factor of 20. The advantage of this work is to achieve a high Q factor, wide continuous tuning range with a simple process for implementation. The tuning ratio is 5:1 at 16 GHz, which is higher than previous works. This inductor operates in a frequency range of 3-20 GHz with a Q of over 5 at its worst case

Chowdhury (2013) presented novel single-device MEMS-based logic gates, such as XOR and AND, for ultra-low leakage computation and for rough environment usage, such as those in highly ionizing radiation and high temperatures and also presented the development of next-generation field-assisted MEMS logic gates for in-situ pull-in voltage compensation/control usually applicable in rough Environments using a unique method of introducing illustrates using ALD SiO_2-Al_2O_3deposition. Also discussed here are MEMS switches for efficient power management that can be integrated easily at low temperature with BEOL VLSI processes, and development of simple, functional circuits designed and fabricated using the single - device MEMS logic gates (XOR and AND)

Deiva (2013) concluded that the design, fabrication and control of the micro robots, current micro robot technology has been reviewed. Based on the review a new type of swimming micro robot for minimally invasive surgery has been proposed. Firstly, the design and structure of the micro robot and EMA coil system is presented. Secondly, the control mechanism for the micro robot has been derived. Then three variables are selected to modify the swimming performance of the micro robot in the control mechanism. Then, by various experiments the optimized values have been found. Developing this technology requires that we address issues such as localization and power. Effective collaboration between medical and robotics experts is required.

Emhemmed and Aburwein (2013) presented a new design of RF-MEMS metal-contact switch and investigate various aspects with depressing the pull-down voltage and subduing the stiction problem by depressing the pull-down voltage. It is also reducing the spring constant by changing the cantilever beam geometry of the RF MEMS switch and overcome the stiction problem by a simple, integrated method using two tiny posts located on the substrate at the free end of the cantilever beam. Also conclude that RF MEMS switch utilize physical contact of metal with low contact resistance to obtain low insertion loss when it actuated, switch is operated at the G-band frequencies with an isolation proposed by the coupling capacitance of the electrodes when the switch is open.

Gmati et al. (2013) worked on RF MEMS continuous reversible variable inductor has been manufactured using microelectronic technology and lamination process. Also evaluate and compare this variable inductor with other work. Inductor is a dual circular coil and has an inductance of few nH. His central idea is to place a liquid droplet between the metal turns of a coil in order to modify the capacitive coupling between metal tracks to change the stored magnetic energy. The SU-8 resin used to realize the micro fluidic channels and Au as metallic tracks and found the range of the inductance is around 107 % at 1.6 GHz,.

Kaul et al. (2013) determined RF MEMS has been reviewed from a device perspective. Devices reviewed reconfigurable circuits, filters, shifter, phase, antenna, integrated inductors, capacitors, tunable and include switches also surveyed packaging techniques for MEMS devices were also surveyed. Good insertion loss and isolation parameters have been surveyed in RF MEMS switches by using silicon bulk micromachining, a wideband spurs-line band-stop filter is described. In addition, development of micro machined, low pass filters are also described.

Maity et al. (2013) represented a methodology for the analysis of the fabrication process of an RF MEMS switch by using two wafers. It had fabricated 15 switches as a batch fabricated in a single arrangement. It has overcome the different fabrication problems of RF MEMS switches.

Singh (2013) analyzed the effect measurement of fixed- fixed beam MEMS calculate the stresses, pull-up voltage with the using of FEM analysis and also concluded the advantages over the using of semiconductor in place of metal element calculate Thea von misses stresses and deflection in semiconductors.Using COMSOL and Ansys software.

Singh et al. (2013) proposed a design which structure is see saw type to overcome the stiction problems in MEMS switches because the insufficient elastic force in the membrane it has high di-electric material and Substrate is Quartz. See-saw type design gives stiction-free operation in the metal to metal contact switches, and gives a switch with high reliability. Also used very uniform and the small gap between the electrodes for achieving flat silicon membrane and a pivot for seesaw mode operation, which helps in achieving a low actuation voltage.

Ali and Feng (2014) adopted on micro/nano-electro-mechanical system (MEMS/NEMS) reliability is, of necessity, due to the fact that we are looking an era in which MEMS and rising NEMS are anticipated to have a major effect on our lives. Over the last decade, important attempts have gone into the reliability study of MEMS/NEMS. Bankruptcy themes in micro- and Nano scales can be came up to by electrical, chemical, thermal factors, mechanical or combinations of them, which can occur during dissimilar fabrication and post-fabrication forms. This paper reviews and contains the dependability issues of MEMS and NEMS in different phases of their life cycles, including fabrication, pattern, logistics, and functional. This paper surveys the common failure modes and mechanisms (i.e., wear, degradation, stiction, adhesion, distortion, packaging, contamination, and electrical failure modes), the dependability prospects of design and manufacturing, as well as dependability evaluation and testing techniques for MEMS/NEMS. An extended ingathering of papers was chosen and integrated to cover various studies in this area, in order to provide a suspicion and perceptivity for researchers who are interested in dependability explore of MEMS/NEMS. Systematic literature research shows the lack of inquiry in system-level and probabilistic dependability analysis for MEMS/NEMS. As reviewed in this survey, applications of MEMS/NEMS, have been widely expanded over the last decade; thus, MEMS/NEMS devices need to exhibit high dependability. Although as yet incomplete, our knowledge of the dependability of MEMS is becoming mature, but a lot of research is required for understanding the relevant dependability issues of NEMS devices. For both MEMS and NEMS devices, there is a lack of research on the system-level reliability. Furthermore, the probabilistic reliability analysis for MEMS/NEMS is another area that demands much more attention from reliability research community to fill the gap. In spite of several research studies reviewed, the growth of methodologies for speeding up life testing techniques and burn-in analysis is of essential importance to ease further commercialization of MEMS/NEMS devices.

Giacomozzi et al. (2014) proposed RF MEMS chip capping to protect sensitive devices by quartz caps having a cavity to enclose MEMS devices and an epoxy film polymer as a sealing ring. Full hermeticity is not possible due to the permeability of the polymer but the goal to protect the mobile parts of the devices during dicing and assembling was achieved. Good RF MEMS devices are produced by die-to-die bonding and a reliable fabrication process is determined. Spell wafer-to-wafer process still needs improvement to increase the fabrication yield. The manufacturing process for both die-to-die and wafer-to-wafer 0-level capping is demonstrated. Good adhesion of caps to the substrate is presented by shear tests, Spell RF measurements on CPW lines show a negligible insertion loss increment. The capping of both capacitive and Ohmic contact switches is reported showing no loss of functionality but a modification of actuation voltage induced by thermal treatment. Also concluded that Shear test measurements show good adhesion of the bonded cap and RF characterization on CPW lines demonstrates that capping does not result in an increase of the insertion loss, Spell the small change of return loss due to impedance mismatch can be compensated by a proper design. Measurements on both capacitive and Ohmic switches, indicate no negative effects of the cap on capacitance and contact resistance, but modification of actuation voltage due to stress induced by the thermal treatment during the cupping process.

CHAPTER 3: PRESENT WORK

3.1 PROBLEM FORMULATION

In this chapter, it is describing the process of design and modelling of RF MEMS switch, how the framed design is feasible and modelling through software as well as shows the mathematical relations on MEMS capacitive shunt switch. After literature rewiew, the following problems need to be formulated:-

- Sticking is the problem which is generally occured during the capacitve switch because of its fixed – fixed nature.
- Due to small in shape formation, the static overload is found on capacitve switch
- The bond b/w the molecular is broken due to penalty of time and composite materials of CPW. In this regard, it can be overcome by using different materials in design on MEMS.
- Creep is the general failure of all materials, it can not neglected but there is possibility to overcome the failure.
- Environmental attack is the natural cause of failure and as resulted moisture is damaged the surface of switch and it could be removed to apply the moisture resistant materials.
- Fatigue is another failure occured due to excessive amount of service cycle of switch and so it can be removed by fatigue resistant operation.

3.2 GAPS IN PREVIOUS RESEARCH

After going through the literature survey, some of the research gaps have been identified.

- There are many design proposed during literature survey all researchers try to make their design more relevant, after survey there are possibility to Work on a more revalent design of MEMS.
- During the literature survey it was found that Mostly MEMS devices have a stiction problem which cause failure of device, so there is work on removing the stiction problem.
- There are more possible work should done on designing the MEMS device which can help to reduce contact forces and also stress gradient.
- After going through the literature survey it was found that RF MEMS switches is design only for microwaves application(x- band , k–band).

3.3 OBJECTIVES FOR THE PRESENT STUDY

(i) To make a Novel RF-MEMS switch that can transfer Radio frequency wave through it, also the analysis, fatigue resistance operation, basically it is making capacitive shunt switches mounted on Coplanar Waveguide (CPW). The need of shunt capacitive switches be fitted for frequency of (3-100 GHz). A good designed shunt capacitive switch gives low insertion loss up to (0. 04 -0. 1 dB) at (5-50 GHz) in the upstate position and also the isolation of (more than 20 dB at (11–51 GHz) in the down state position we are trying to achieve this in our design.

(ii) To frame a device for less stress concentration in respect to the maximum removal of sharp edges. As many of switches having sharp curve edges that increasing more stress concentration between two adjacent faces so that an approach can be proposed to this problem that will be resolved it by using curves or bevel edges.

(iii) To form a non-conductive coating on the stiff membrane to cover the conductive material. Because there is no such provision of coating over membrane for resisting the moisture content and fatigue. The present study will propose the formation of coating on the MEMS Bridge (stiff membrane).

(iv) To apply COMSOL 5.0 Multiphysics and CATIAV5 Softwares for simulation of RF MEMS Design. The designing is to be performed on COMSOL and CATIA V5 as well and the analysis will be performed by COMSOL.

3.4 METHODOLOGY

In this section, the method and mathematical formulation is defined which is applying in present study and also addressed to designing of CPW and membrane.

3.4.1 Capacitive Shunt Switch

The Switch is having a height (g) above the dielectric layer of T-line and the dielectric thickness is (t_d) with a dielectric constant of (ε_r), the switch is (L) mm long, (w) mm wide. (t) mm thick.

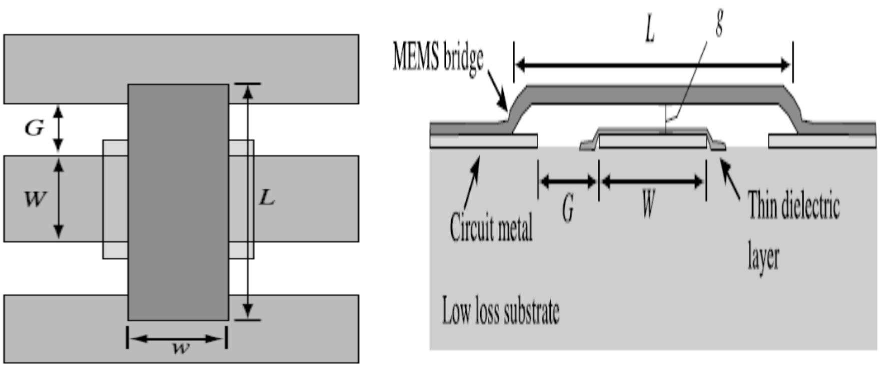


Figure 3.1: Capacitive Switch Configuration

The width of T-line is W mm (Rabiez, 2002). A substrate GaAs, LTCC, alumina or quartz dielectric the MEMS shunt switch, subjected in coplanar waveguide or micro strip topology. In a CPW configuration, MEMS is connected through a CPW ground plane. A shunt capacitive switch is shown in Figure 3.1. The T- line is subjected to an electrostatic force that induced the membrane towards the T- line due to die electric layer consentaneously increasing the capacitance when DC voltage is applied between stiff membrane (MEMS Bridge), this capacitance will connect the T-line and blocked (Short circuit) the incoming signal. When the voltage is removed, the membrane regained its original position due to its stiffness.

3.4.2 MEMS Capacitive Shunt Switch Circuit Model

The signal line having a length of (w/2) + ℓ, where ℓ=20 μm distance from the reference plane to the edge of the stiff membrane. Generally, values of micro-wave switches are a capacitance of 30 fF/2.5 pF, an inductance of 5–18 pH, and a series resistance of 0.1–0.3 Ω (Rabiez, 2002). The Switch's impedance is given by

$$Z_s = R_s + j\omega L + \frac{1}{j\omega C} \quad (3.1)$$

With C = C_u or C_d depends upon their positions of the switch. The resonant frequency is

$$f_0 = \frac{1}{2\pi}\frac{1}{\sqrt{LC}} \quad (3.2)$$

The cutoff frequency is determined

$$f_c = \frac{1}{2\pi C_u R_s} \quad (3.3)$$

Figure 3.2 shows the CLR modal od the device below,

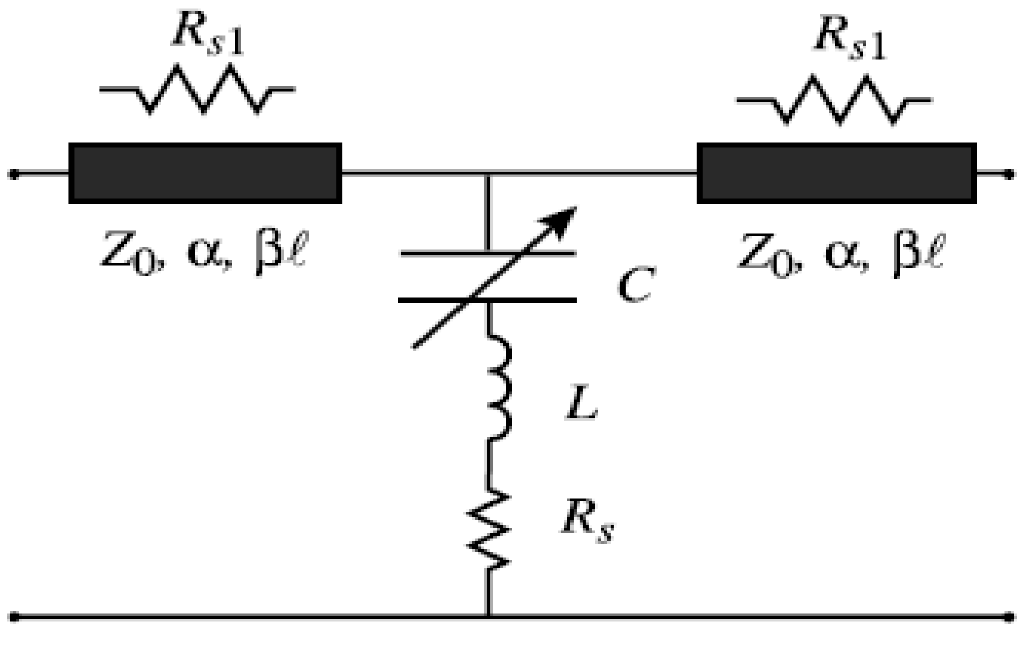


Figure 3.2: CLR Model

3.4.3 Electromagnetic Modeling of MEMS Shunt Switch Upstate Capacitance

Rabiez (2002) defines the parallel-plate capacitance of the MEMS shunt switch is,

$$C_{pp} = \frac{\varepsilon_0 wW}{g + \frac{t_d}{\varepsilon_r}} \tag{3.4}$$

The denominator term is due to the finite thickness of the dielectric.

For a thickness of dielectric 1500 Å, the upstate capacitance is also derivable using software such as Sonnet, HFSS,Ansys and IE3D. If dielectric layer is neglected, then the height should be (g). Downstate Capacitance and Capacitance Ratio, ,

Down state Capacitance (C_d)

$$C_d = \frac{\varepsilon_0 \varepsilon_r A}{t_d} \tag{3.5}$$

Capacitance Ratio (C_d/C_u)

$$\frac{C_d}{C_u} = \frac{\frac{\varepsilon_0 \varepsilon_r A}{t_d}}{\frac{\varepsilon_0 A}{g + \frac{t_d}{\varepsilon_r}} + C_f} \tag{3.6}$$

3.4.4 Design of CPW (Coplanar Wave Guide)

CPW is the base of RF MEMS device which is fabricated to micromachining of either semiconductor or non-conducting materials on CPW have Two Grounds and one t-line which is probably same as the length of the MEMS Bridge, CPW is the Stationary Part where whole mechanism is set on it. Figure 3.3 shows the structure of CPW.

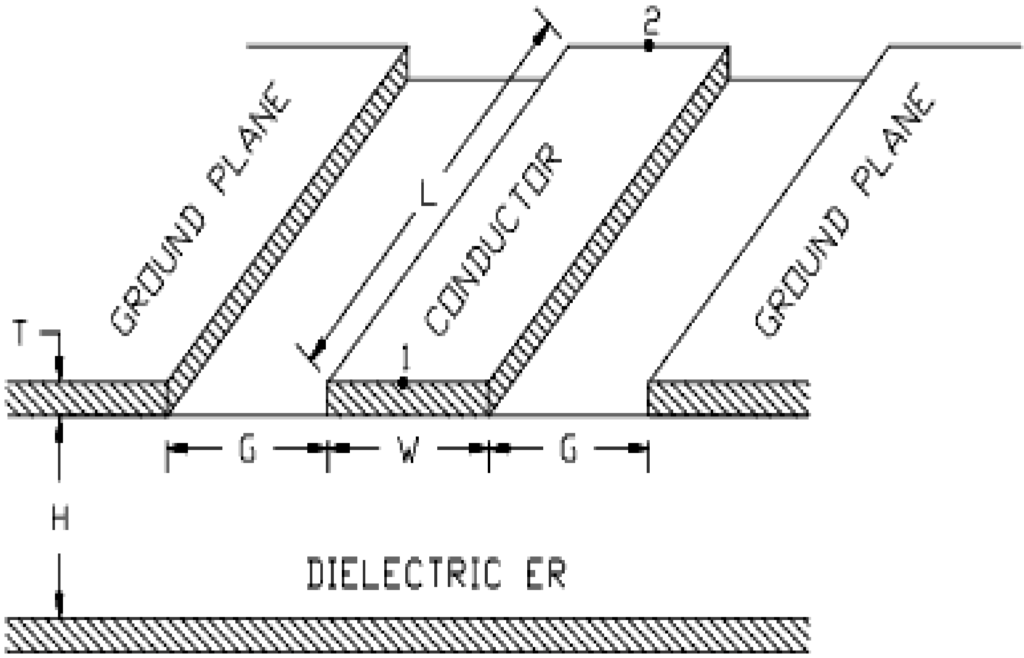


Figure 3.3: Coplanar wave Guide (CPW)

Most fabrication processes can be realized on any substrate with a semiconductor grade finish, such as glass, quartz, silicon, GaAs, InP, and so on. In present study, it is being using BN CA grade specification of BN and having three grades as follows:-

(i) BN (BO) Boric Oxide absorbs moisture.

(ii) BN (CA) Calcium Borate has good moisture resistance.

(iii) BN (XP) contains no binder, used for extreme of temperature (pure).

It is using BN CA grade because it has good moisture resistance. Dielectric layers is also coating on CPW Grounds and it could be 1000-1500 Å as thickness layers in used but present research work adopting AlO_2**.** HiO_2 have good dielectric property compare to all and give better effect either if it's small thickness. More detailed specification of Boron Nitride CA Grade is mentioned in Table 3.1.

Table 3.1: Specification of BN CA Grade

Mechanical	SI / Metric	Orientation of Pressing Direction			
		Parallel		Perpendicular	
Density	gm/cc(lb/ft2)	1.9	(120)	1.9	120
Color		White		White	
Elastic Modulus	GPa ($lb/in^2 x10^6$)	33.8	(4.9)	75	10.9
Compressive Strength	MPa ($lb/in^2 x10^3$)	30	(4.4)	44.5	6.5
Thermal conductivity	W/m°k	27	187	31	215
Coefficient of Thermal Expansion	10^{-6}/°k (10^{-6}/°F)	2.95	(1.6)	0.87	0.5
Dielectric Strength	ac-kv/mm (volts/mil)	67	(1700)	………	

3.4.5 Design of MEMS Bridge

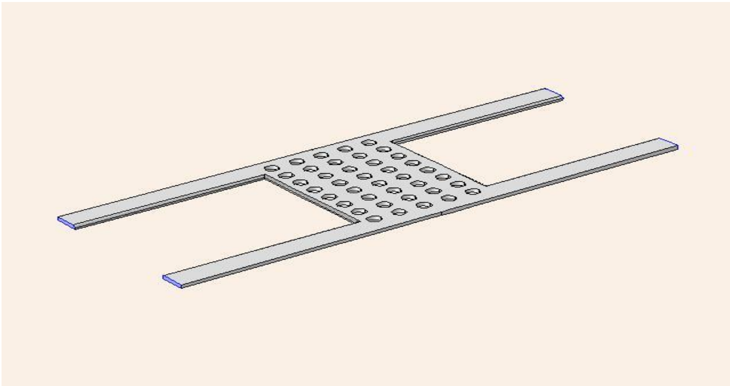


Figure 3.4: Fixed-Fixed Membrane for Capacitive Actuation

MEMS Bridge or stiff membrane is the main part of MEMS which is mainly the actuation part of the whole body. The present study is adopting the electrostatic actuation between dielectric and membrane. Membrane 1 parameters specifications are mentioned in Table 3.2.

Table 3.2: Global Parameters for Membrane 1

Name	Expression	Value	Description
V0	1[mV]	0.0010000 V	Initial Voltage
Vstep	5[V]	5.0000 V	Voltage Step
insheight	100[nm]	1.0000E-7 m	Insulator height
airheight	900[nm]	9.0000E-7 m	air height
en	1e15[Pa/m]	1.0000E15 N/m³	spring stiffness
tn	5e5[Pa]	5.0000E5 Pa	Contact Force

Figure 3.5 depicts the material of a membrane is “aluminium” and the dimension of membrane is 220x100x1µm. The holes are provided to reduce the squeeze film damping and increasing the switching speed of the MEMS switch and these are the membrane view angles.

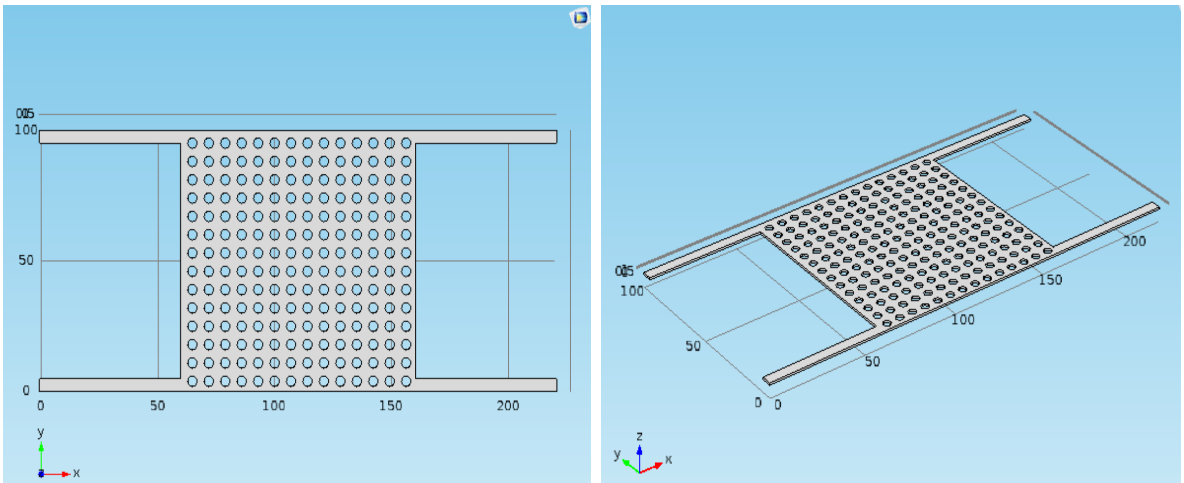


Figure 3.5: Geometrical Design of Fixed-fixed Membrane

3.4.6 Design Procedure on Comsol 5.0 Multiphysics Software

COMSOL Multiphysics is a finite element analysis, solver and Simulation software / FEA Software package for various physics and engineering applications, especially coupled phenomena, or multiphysics. COMSOL Multiphysics also offers an extensive interface to MATLAB and its toolboxes for a large variety of programming, preprocessing and post processing possibilities. The packages are cross-platform (Windows, Mac, Linux). Furthermore, ANSYS dimensional parameter is in metrics, otherwise COMSOL can perform in metrics and micrometers. COMSOL is specially framed with MEMS module which is not available in ANSYS and CATIA. Also, in addition to conventional physics-based user interfaces, COMSOL Multiphysics also allows for entering coupled systems of partial differential equations (PDEs). The PDEs can be entered directly or using the so-called weak form (see finite element method for a description of weak formulation). An early version (before 2005) of COMSOL Multiphysics was called FEMLAB. First, make a Coplanar Waveguide on Console window and adding the material with the help of material library which is given to COMSOL library.

Step by step simulation procedure is described as follows,

i) Defining Physics.

Start by selecting the space dimension for your model component: 3D, 2D Axisymmetric, 2D, 1D Axisymmetric, or 0D.

ii) Defining Geometry.

Geometry decides whether modal in mm , µm and m etc. it provides tools to make a proper design itself and also an option to import geometry through the other convectional Software.

iii) Defining Material.

It has some preloaded material tree where all material is present also their property, material tree helps to find MEMS Material and make less effort to define their properties.

iv) Setting Up Physics.

In here when the geometry and materials are defined, the boundary conditions are going to be set like, fixed constrain, boundary load etc.

v) Meshing.

The mesh settings determine the resolution of the finite element mesh used to discretize the model. The finite element method divides the model into small elements of geometrically simple shapes, in this case tetrahedrons.Comsol (2012) In each tetrahedron, a set of polynomial functions is used to approximate the structural displacement field—how much the object deforms in each of the three coordinate directions.

vi) Simulation and Study.

At the beginning of setting up the Physics it selected a Stationary study, which implies that COMSOL will use a stationary solver. For this to be applicable, the assumption is that the load, deformation, and stress do not vary in time. The default solver settings will be good for this simulation if your computer has more than 2 GB of in-core memory (RAM). If you should run out of memory so more complex the design more ram will used.the whole process of Study is depends upon in Meshing either fine or coarse.

v) Results.

The von Mises stress is displayed in the Graphics window in a default Surface plot with the displacement visualized using a Deformation subnode. Change the default unit (N/m2) to the more suitable unit MPa.

Figure 3.6 gives the information about the whole Designing procedure are going to be done in this thesis on Flow chart and algorithm form.

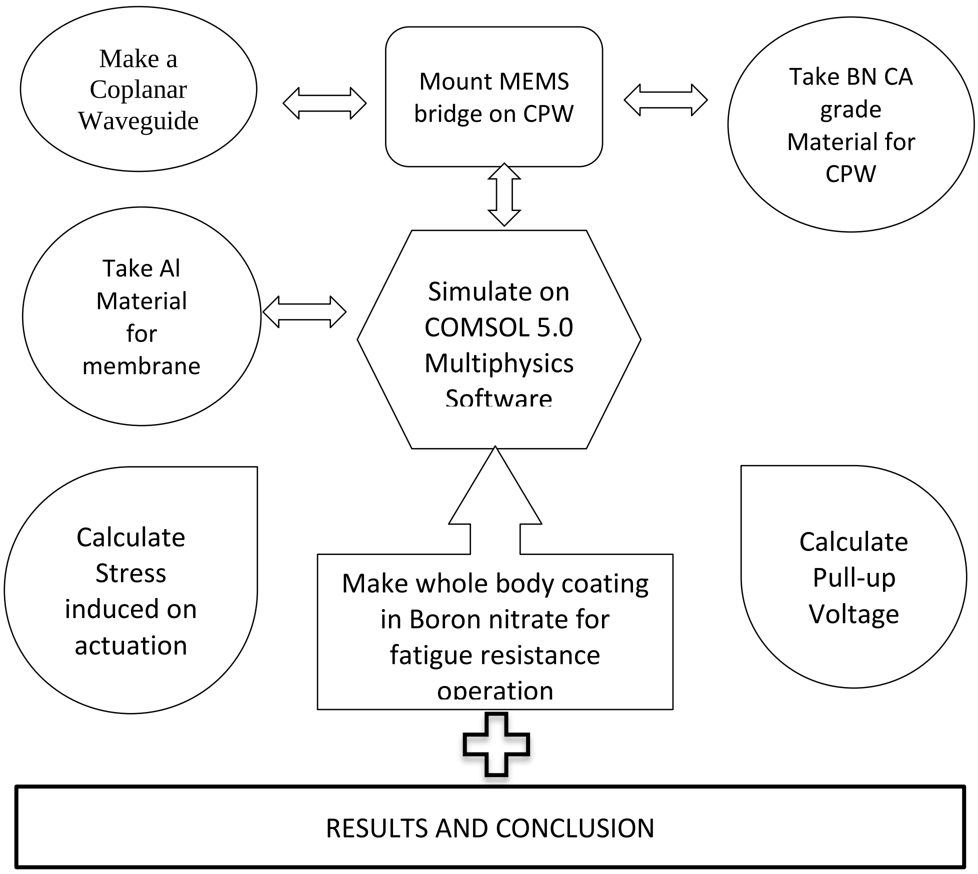


Figure 3.6: Flow Chart of Complete Design Procedure

Figure 3.7 describes simulation steps to be adopted in COMSOL Multiphysics Software presented research work in the form of system architecture algorithm.

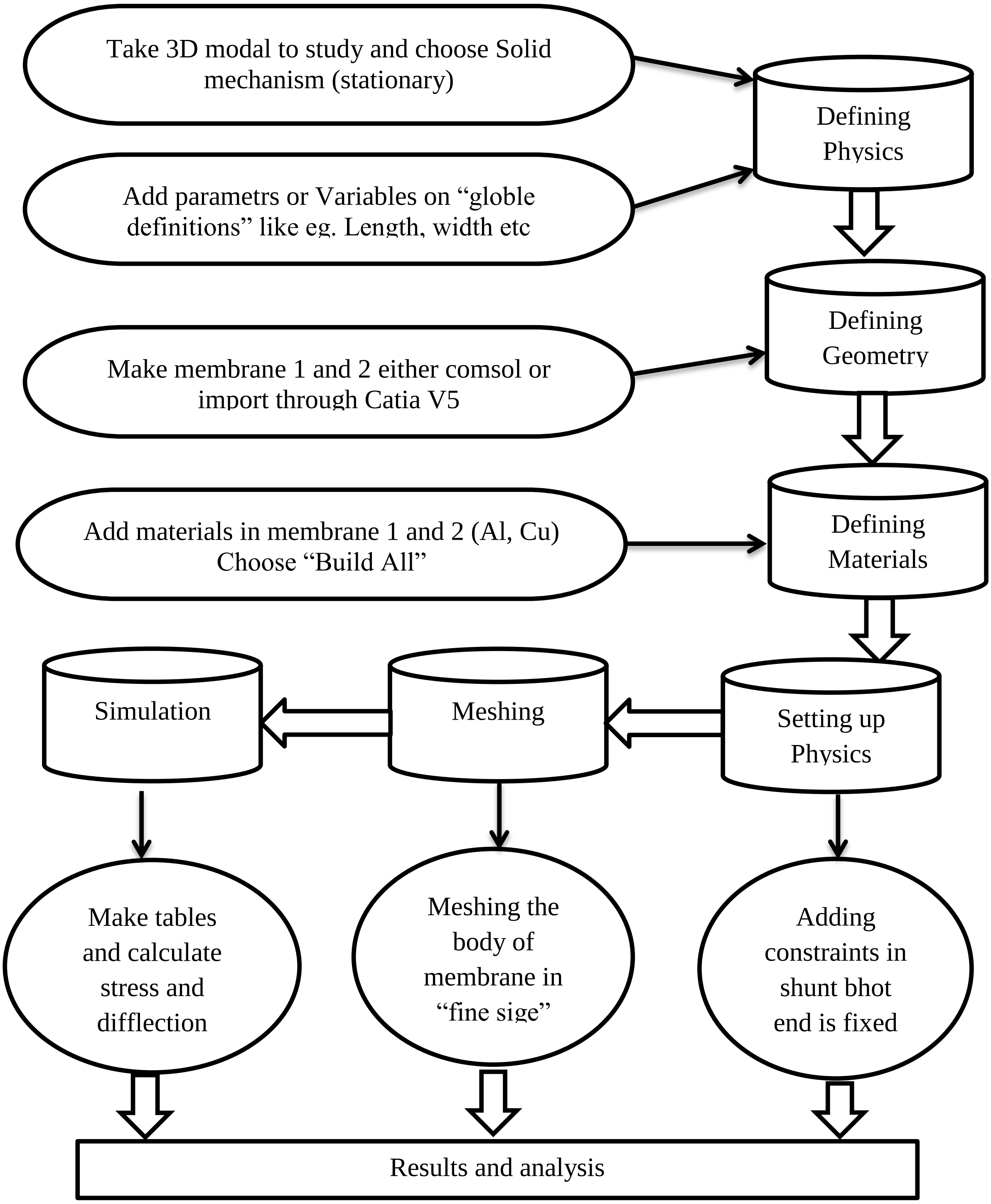


Figure 3.7: System Architecture Algorithm of Simulation Steps in Comsol 5.0 Multiphysics

CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents the results that are based on the calculations of von Misses stress, displcement of membrane in solid mechanism interface and also the electrostatic displacement, pull in voltage, contact force after the electromechanism and study interface of Comsol 5.0. Also shows step by step simulation and modelling process of COMSOL 5.0 Software and its uses as well.

4.1 SYSTEM IMPLEMENTATION

The CAD tools in COMSOL Multiphysics offer many prospects to create geometries using solid modeling and boundary modeling. This chapter covers geometry modeling in RF-MEMS in COMSOL Multiphysics as shown in Figure 4.1. In addition, it is shows the modelling of the membrane which is done by COMSOL 5.0.

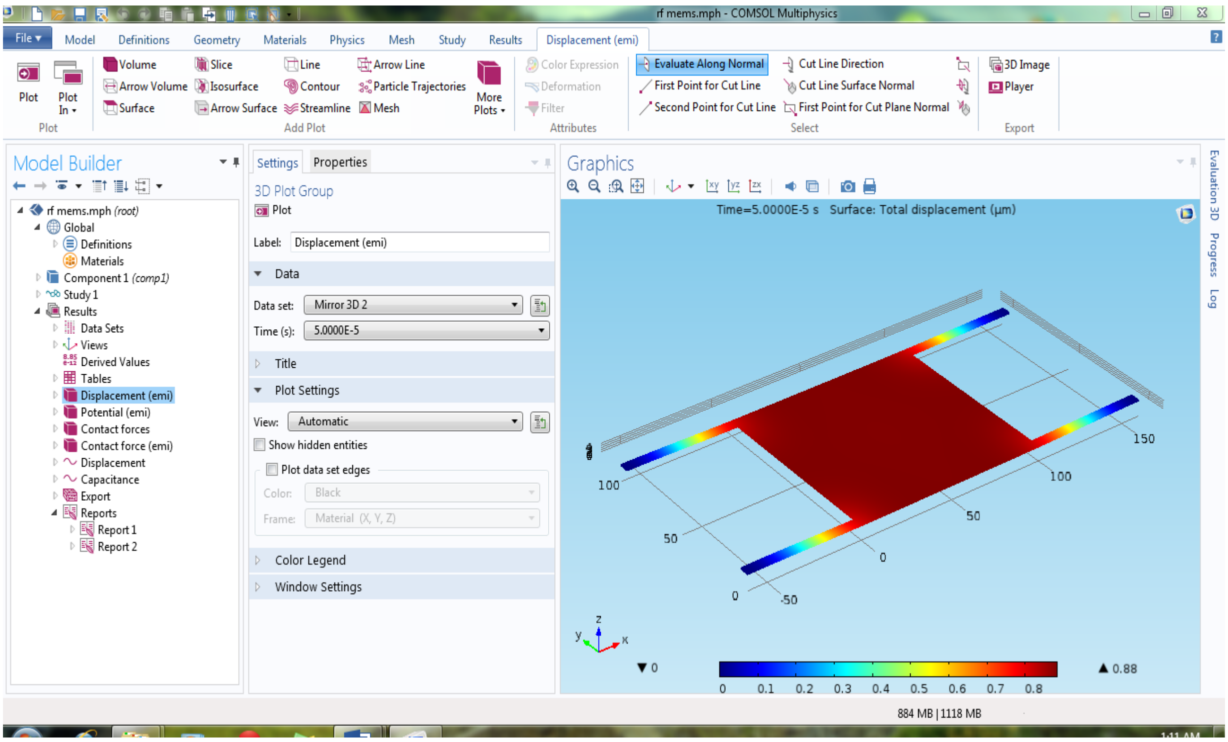


Figure 4.1: COMSOL 5.0 Multiphysics Interface

4.2 DEFINITONS

This section defines as the global definition section where the whole process parameter, also variable is define on that interface.

4.2.1 Parameters

This section helps to define the input parameters where these parameter is further used by whole geometry during simulation.

Table 4.1: Input Parameters in COMSOL 5.0

Name	Expression	Value	Description
V0	1[mV]	0.0010000 V	Initial Voltage
Vstep	5[V]	5.0000 V	Voltage Step
insheight	100[nm]	1.0000E-7 m	Insulator height
airheight	900[nm]	9.0000E-7 m	air height
en	1e14[Pa/m]	1.0000E14 N/m³	spring stiffness
tn	5e5[Pa]	5.0000E5 Pa	Contact Force

4.2.2 Variables

These are parameters where value is depend upon its another value, there are two types of variables, global variables and local variables in similar manner as parameters and functions. Global variables are available in all the models in a file, whereas local variables are defined in the context of an entire model (geometry) or for specific domains, edges, boundaries or points.

Table 4.2: Varaibles of MEMS Geometry

Name	Expression	Description
Gap	airheight + w	Distance b/w membrane and di-electric
Contact pressure	(gap<=0)*(tn - en*gap) + (gap>0)*tn*exp(-gap*en/tn)	Operating pressure
Va	V0 + Vstep*step2(t/1[s])	Applied voltage

4.3 IMPLEMENTATION OF FUNCTIONS IN COMSOL

There are three extensive categories of functions Interpolation, Analytic and Piecewise and a number of templates for common function types, such as step and ramp functions . it can also create external function interfaces to include functions written in C and MATLAB. Functions can be global or local in scope, although two function types external functions and MATLAB functions can only be defined globally.

4.3.1 Step Function

Step function is a sharp transition from 0 to some other value (amplitude) at some location (a certain time). Create a single step function with a certain amplitude from an initial level to a final level at a start location. This step function is a function of one variable (the time t). There are two steps used which are shown in Figures 4.2 and 4.3.

(i) Step 1

Step 1 shows the height of the transition layer of di electric height partially, shows on Figure 4.1,

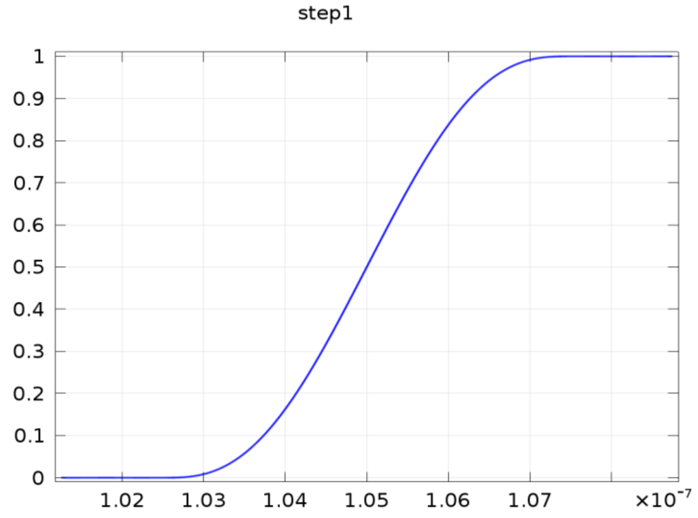


Figure 4.2: Step1 Function Graph in COMSOL

COMSOL commands;

Step Parameters

Name	Value
Location	1.05*insheight
From	0

Smoothing Zone Operator

Name	Value
Size of transition zone	0.05*insheight

(ii) Step2

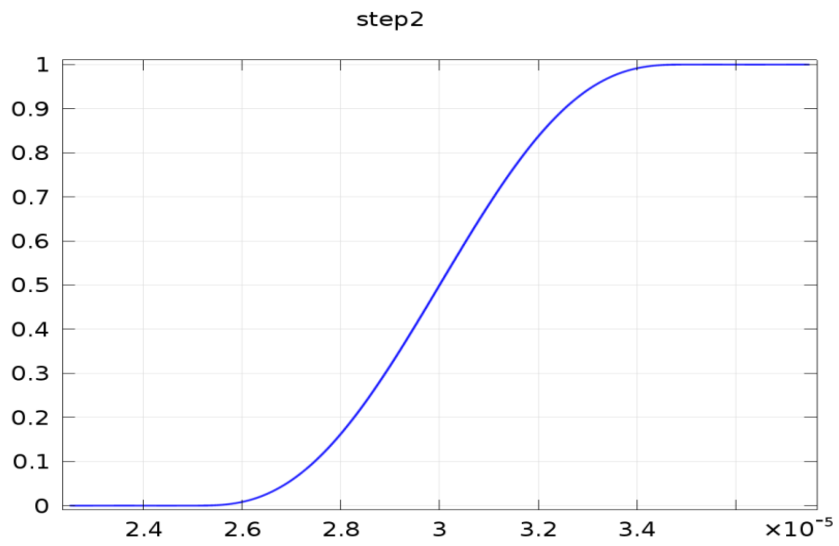


Figure 4.3: Graph of Step2 Function

Step 2 define the width of the dielectric partially, it is shows on Figure 4.2,

Commands in COMSOL 5.0;

Step-2 Parameters

Name	Value
Location	3e-5
From	0
To	1

Smoothing Zone Operator

Name	Value
Size of transition zone	1e-5

4.4 SELECTIONS AND DEFINING FOR GEOMETRY OF RF MEMS

Selection is a section where the geometry will be define during the process of simulation but in electrostatic interface the selection of domain and boundaries is define by the user. In here there are several selection is made below;

(i) Bridge

The Bridge is membrane of switch where it can explicit between di-electric and Gap figure 4.3 is shows bridge(membrane) in software interface.

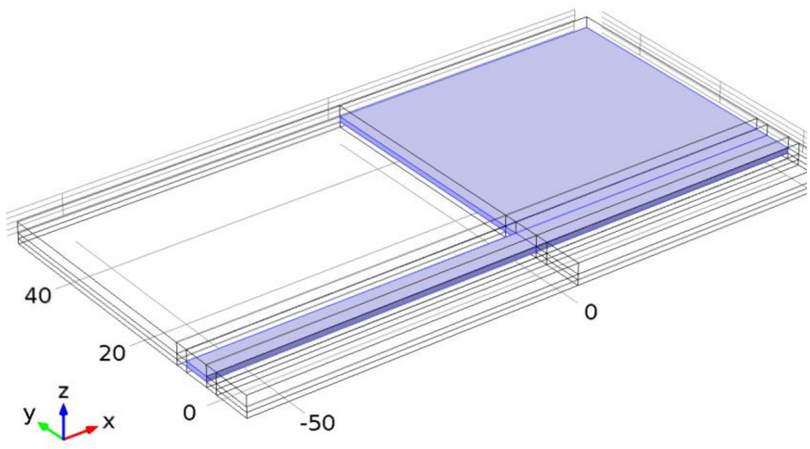


Figure 4.4: Selecting the Bridge on COMSOL

(ii) Gap

Top side domain of the geometry which is 2 µm in distance which is surrounding on membrane bridge. Figure 4.5 shows the domain on gap,

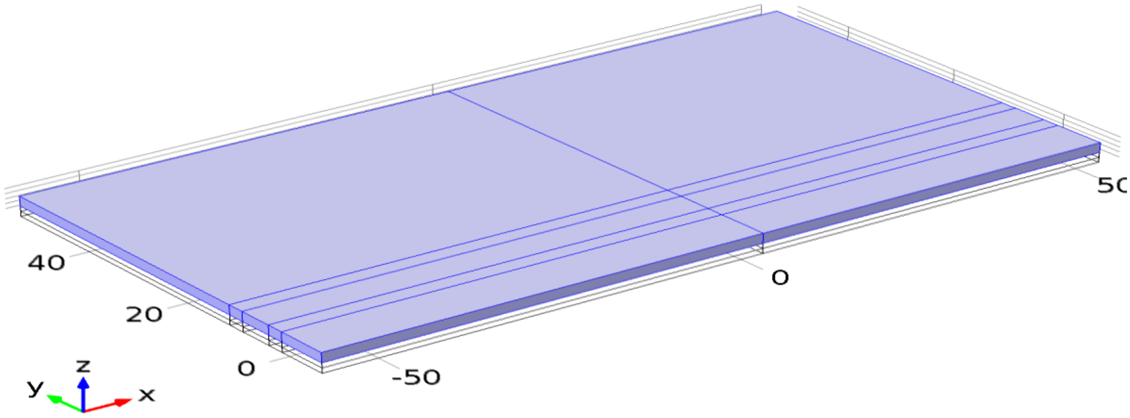


Figure 4.5: Selecting Gap of Membrane on COMSOL

(iii) Bridge Surface

It is the surface of membrane where the voltage is applied through is surface so the Adjacent funtion is used to define its boundary condition.shows in Figure 4.6,

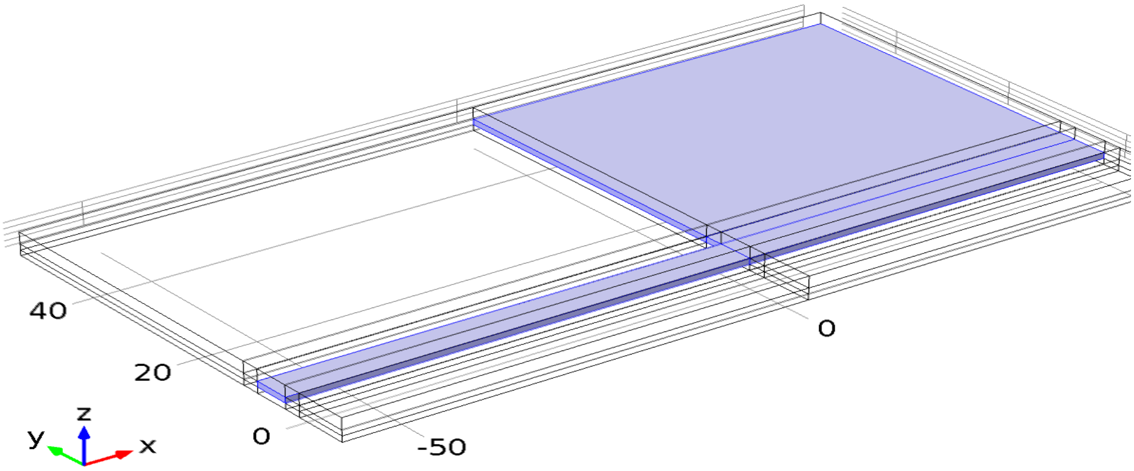


Figure 4.6: Selecting Bridge Surface on COMSOL

COMSOL 5.0 Command is below:

Selection type
Adjacent

Selection
Boundaries 24–26, 29, 35, 78–79, 82, 87, 89, 92, 97, 99, 102, 105, 114, 117, 120

Input entities

Name	Value
Geometric entity level	Domain
Input selections	Bridge

Output entities

Name	Value
Geometric entity level	Adjacent boundaries

(iv) Base

Selecting the surface of the whole geometry where the CPW and di-electric exists.shows in Figure 4.7,

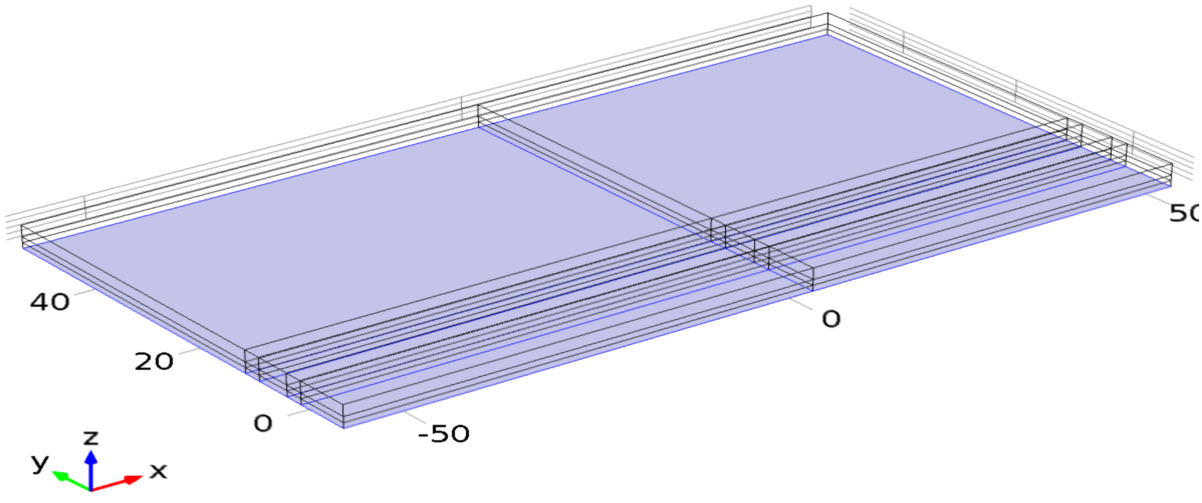


Figure 4.7: Selecting Base of Geometry in COMSOL

Command of COMSOL 5.0 is below,

Selection type
Box

Selection
Boundaries 3, 13, 23, 33, 43, 56, 66, 76, 86, 96

Geometric entity level

Name	Value
Level	Boundary

Output entities

Name	Value
Include entity if	Entity inside box

(v) Box 3

This is the lower surface of the domain of where the membrane meet the di electric and t –line so here its use a box function in comsol to define geometry. Figure 4.8 shows the boundary of geometry.

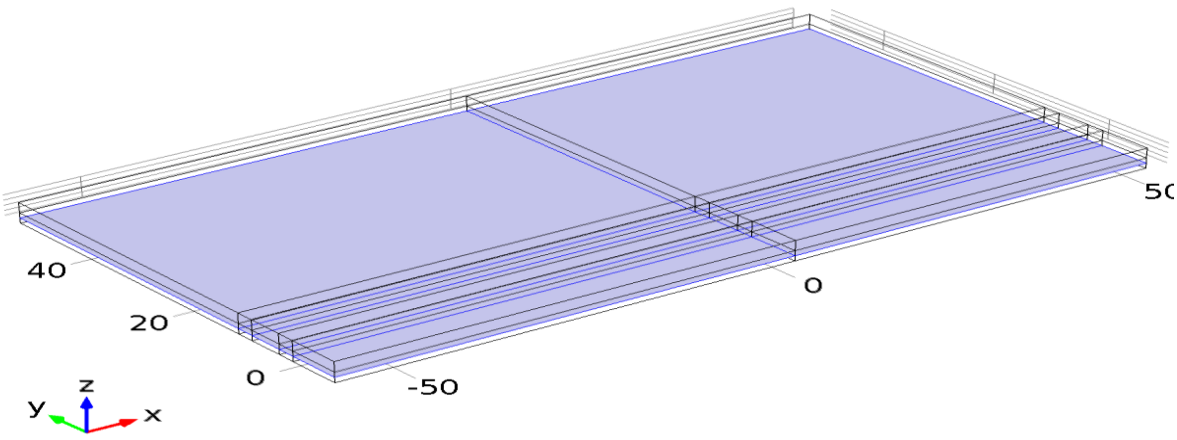


Figure 4.8: Simulate Box3 Boundary in COMSOL

Command in COMSOL 5.0,

Selection type
Box

Selection
Boundaries 6, 16, 26, 36, 46, 59, 69, 79, 89, 99

Geometric entity level

Name	Value
Level	Boundary

Output entities

Name	Value
Include entity if	Entity inside box

(vi) Bridge lower side

It is the domain where the boundary of lower side of bridge is selected for selection of the boundary in comsol it is use intersection funtion because it is the intersection of Bridge surface and Box 3 as depicted Figure 4.9,

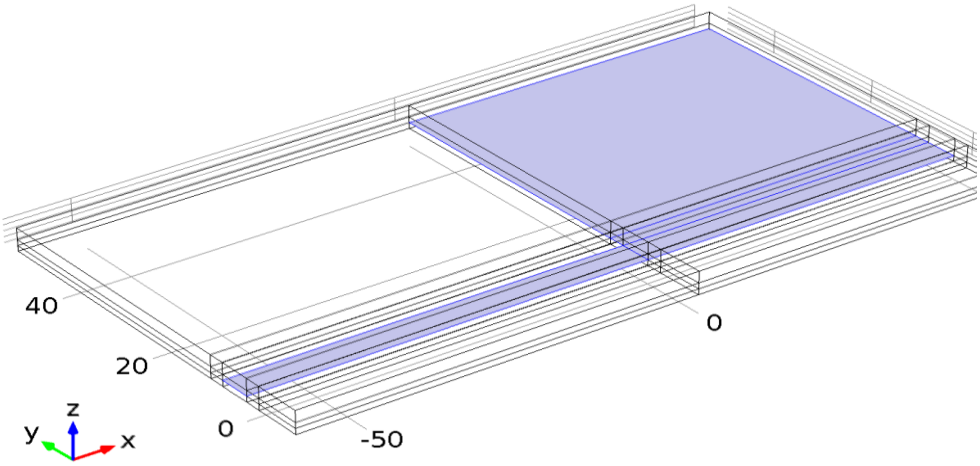


Figure 4.9: Selecting Bridge Lower Side Boundary in COMSOL

Command in COMSOL

Selection type
Intersection

Selection
Boundaries 26, 79, 89, 99

Geometric entity level

Name	Value
Level	Boundary

Input entities

Name	Value
Selections to intersect	{Bridge Surface, Box 3}

(vii) Symmetry

The total geometry of the Switch membrane is the symmetry in nature so comsol have a symmetry function to solve those types of geometry problems in here the geometry have the two symmetry side is x and y axis respectively to select those side Box function is used in comsol Figure 4.10 shows the symmetry boundary,

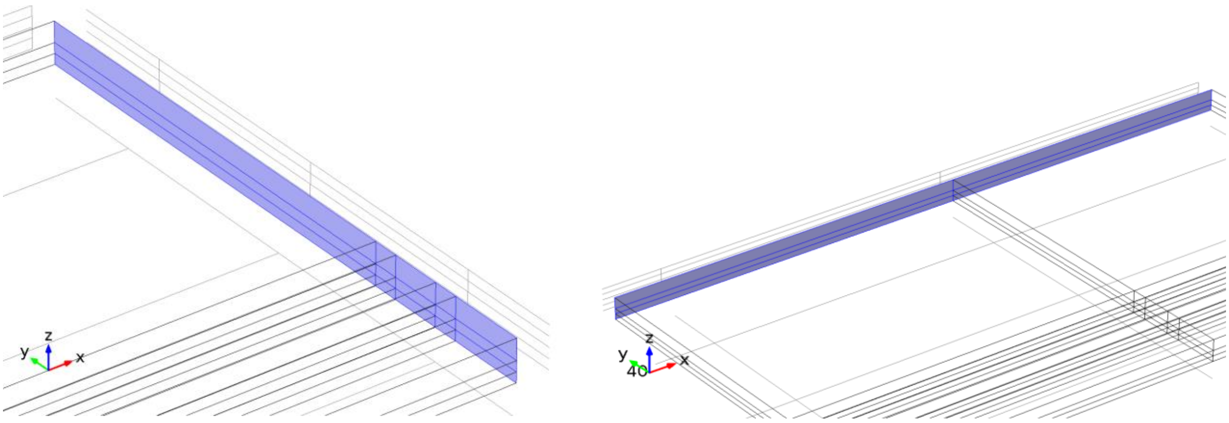


Figure 4.10: Selecting Symmetry Axis of Membrane in COMSOL

COMSOL command is below;

Symmetry x axis

Selection type
Box

Selection
Boundaries 107–121

Geometric entity level

Name	Value
Level	Boundary

Output entities

Name	Value
Include entity if	Entity inside box

Symmetry y axis

Selection type
Box

Selection
Boundaries 51–53, 104–106

Geometric entity level

Name	Value
Level	Boundary

Output entities

Name	Value
Include entity if	Entity inside box

4.5 GEOMETRY AND MODELING OF RF MEMBRANE

Step by step the geometry of the membrane which is made on comsol describe below;

Figure 4.11 shows the geometry of the one forth of membrane

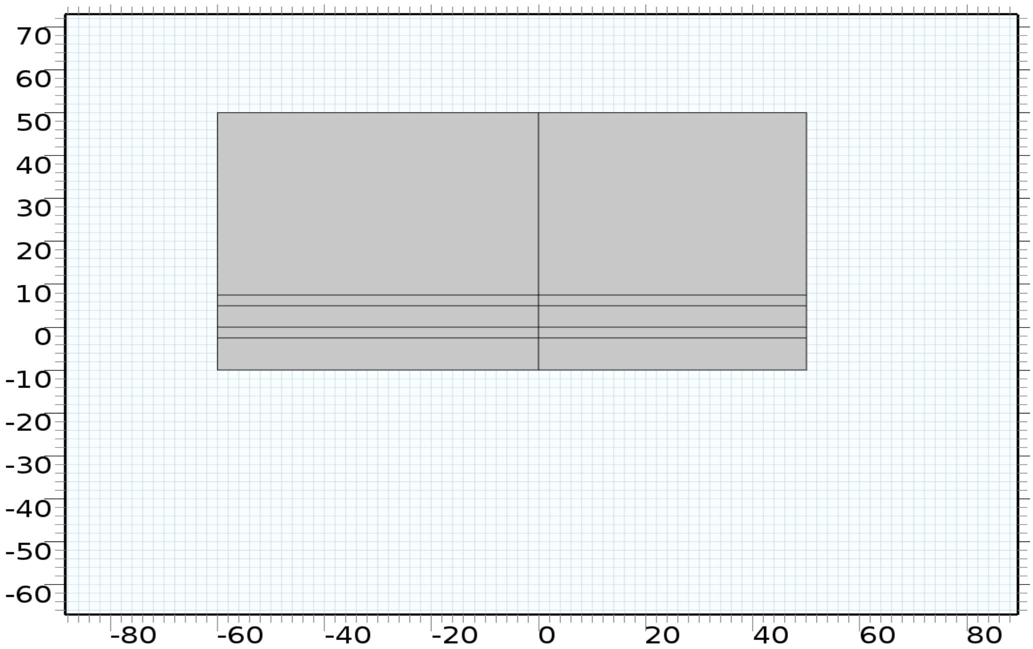


Figure 4.11: Top View of Membrane in COMSOL

Command on COMSOL 5.0

Plane Geometry

(i) Rectangle 1 (r1)

Position

Name	Value
Position	{-60, 0}

Size

Name	Value
Width	110
Height	5

(ii) Rectangle 2 (r2)

Position

Name	Value
Position	{0, -10}

Size

Name	Value
Width	50
Height	60

(iii) Rectangle 3 (r3)

Position

Name	Value
Position	{-60, -10}

(iv)Rectangle 4 (r4)

Position

Name	Value
Position	{-60, -2.5}

Size

Name	Value
Width	110
Height	60

Size

Name	Value
Width	110
Height	10

(v) Extrude 1 (ext1)

Settings

Name	Value
Work plane	Work Plane 1

Distances from plane

Name	Value
Distances	{1, 2, 4}

Displacements

Displacements xw (μm)	Displacements yw (μm)
0	0
0	0
0	0

Scales

Scales xw	Scales yw
1	1
1	1
1	1

Twist angle

Name	Value
Twist_angles	{0, 0, 0}

4.6 MATERIALS OF RF MEMBRANE DEVICE

In this section the selection of material is done on COMSOL interface,so in here there are three seletion is made which is shown on Figures 4.10, 4.11 and 4.12.

(i) Air

Air is used as a gap domain material of geometry which is situated below the membrane of the design. In figure 4.12

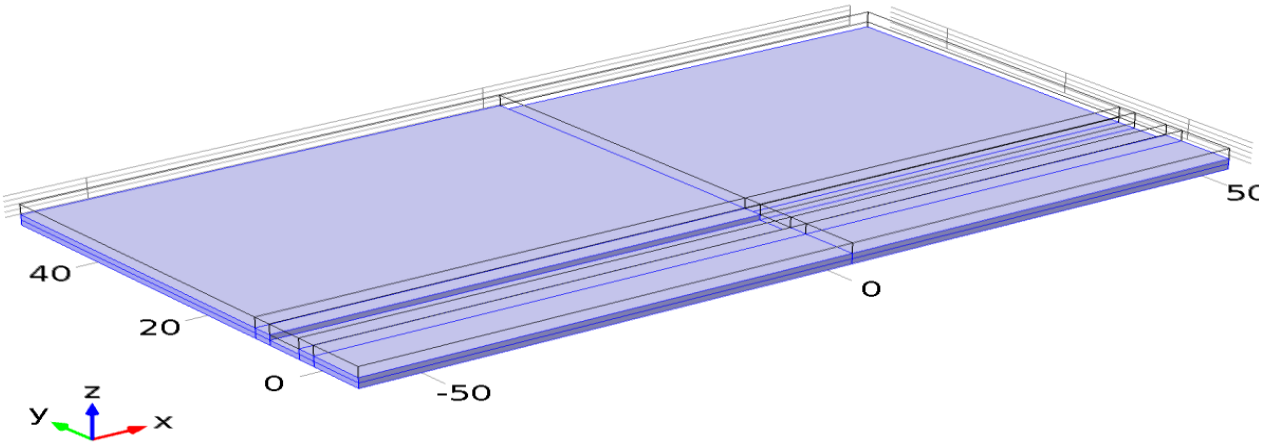


Figure 4.12: Selecting Air as a Material for Gap

COMSOL command;

Selection

Geometric entity level	Domain
Selection	Domains 1–2, 4–5, 7, 10–11, 13–14, 16–17, 19–20, 22, 25, 28

Material parameters

Name	Value	Unit
Relative permittivity	1	1

(ii)Alluminium Oxide (Al_2O_3)

The dielectric material used on the switch is aluminum oxide which is shown above the base of the T-line in Figure 4.13.

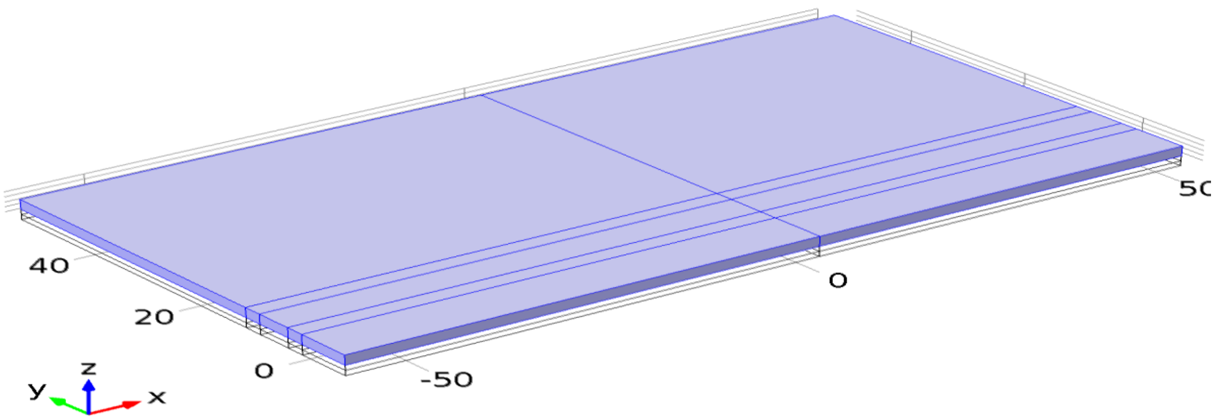


Figure 4.13: Selecting the Material on Dielectric

Command on COMSOL

Selection

Geometric entity level	Domain
Selection	Domains 3, 6, 9, 12, 15, 18, 21, 24, 27, 30

Material parameters

Name	Value	Unit
Relative permittivity	8	1

Basic Settings

Description	Value
Relative permittivity	{{8, 0, 0}, {0, 8, 0}, {0, 0, 8}}

(iii) Aluminum

The material of the membrane is aluminium and the selection of the material is depicted below in Figure 4.14,

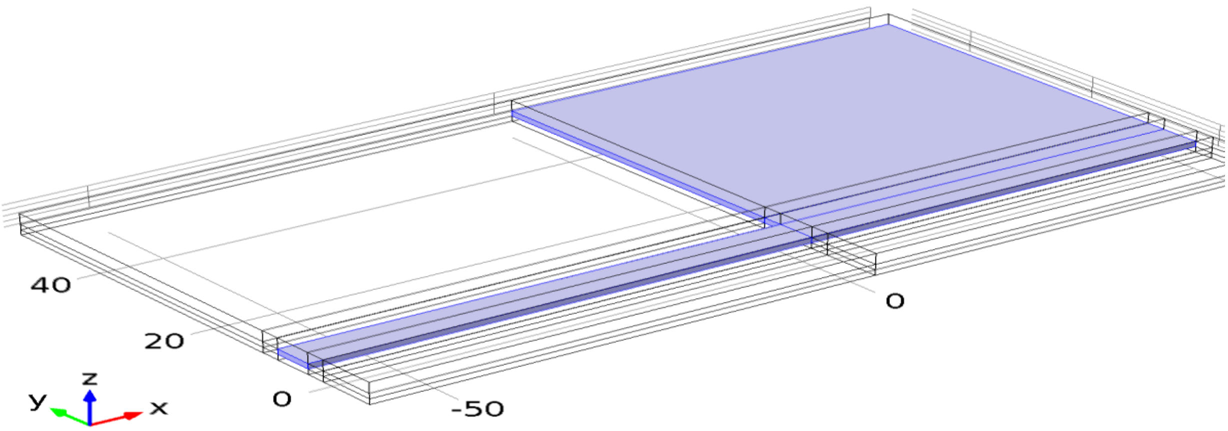


Figure 4.14: Selecting the Aluminium Material on Bridge

Command of the COMSOL is described below;

Selection

Geometric entity level	Domain
Selection	Domains 8, 23, 26, 29

Table 4.3: Material Parameters of Membrane

Name	Value	Unit
Density	2700[kg/m^3]	kg/m^3
Young's modulus	70e9[Pa]	Pa
Poisson's ratio	0.33	1
Density	2700[kg/m^3]	Density
Relative permeability	1	
Thermal conductivity	238[W/(m*K)]	Thermal conductivity
Young's modulus	70e9[Pa]	
Poisson's ratio	0.33	

4.7 APPLICATION OF ELECTROMECHANICS IN RF MEMBRANE GEOMETRY

This is interface is used to done electrostatic analysis in COMSOL 5.0 software and the step by step process is described below and Figure 4.15 shows the interface,

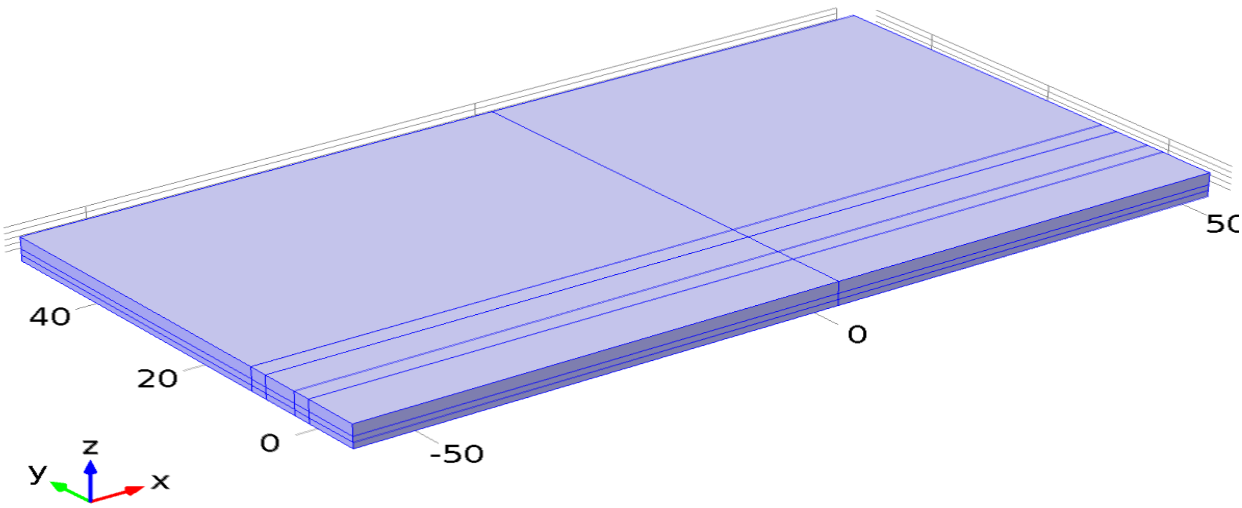


Figure 4.15: Shows the Electromagnetic Interface in COMSOL

Selection

Weak expression	Integration frame	Selection
-test(emi.W_mesh)	Material	Domains 1–7, 9–22, 24–25, 27–28, 30

(i)Electrical Material Model 1

Selection

Geometric entity level	Domain
Selection	Domains 1–7, 9–22, 24–25, 27–28, 30

Equations

$$\nabla.(\varepsilon_0 var^{\varepsilon} r^{E}) = \rho_v \quad (4.1)$$

$$E = -\nabla v \quad (4.2)$$

(ii) Linear Elastic Material 1

Figure 4.16 shows selection of the linear elastic material of membrane,

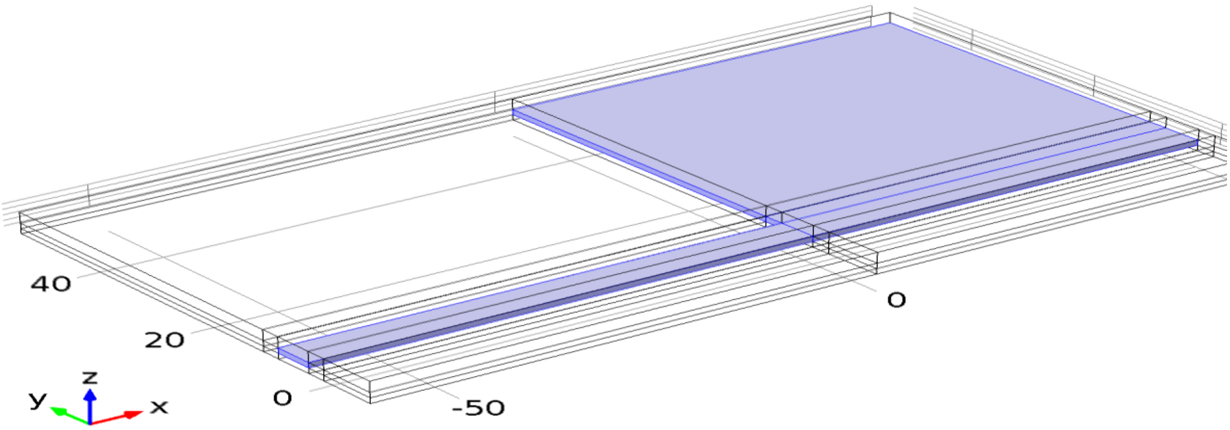


Figure 4.16: Define Bridge as Linear Elastic Material 1

(iii) Fixed Constraint 1

Command on COMSOL

Selection

Geometric entity level	Boundary
Selection	Boundary 24

Equations

$$u = 0 \quad (4.3)$$

Settings

Description	Value
Apply reaction terms on	All physics (symmetric)
Use weak constraints	Off
Constraint method	Elemental

Shape functions

Constraint	Constraint force	Shape function	Selection
-u	test(-u)	Lagrange (Quadratic)	Boundary 24
-v	test(-v)	Lagrange (Quadratic)	Boundary 24
-w	test(-w)	Lagrange (Quadratic)	Boundary 24

Geometry of membrane has four anchor and so here it is one fouth of geometry and the anchor point of the same is shown below in Figure 4.17 and addresses to the fixed domain on membrane,

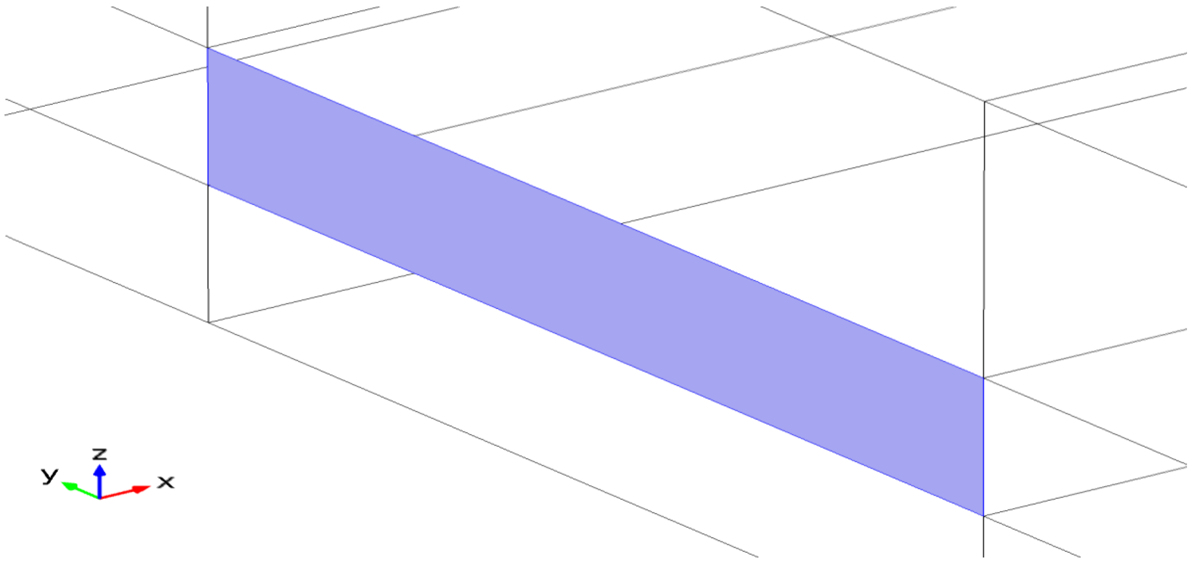


Figure 4.17: Define the Fixed Constraint 1 in COMSOL

(v) Symmetry 1

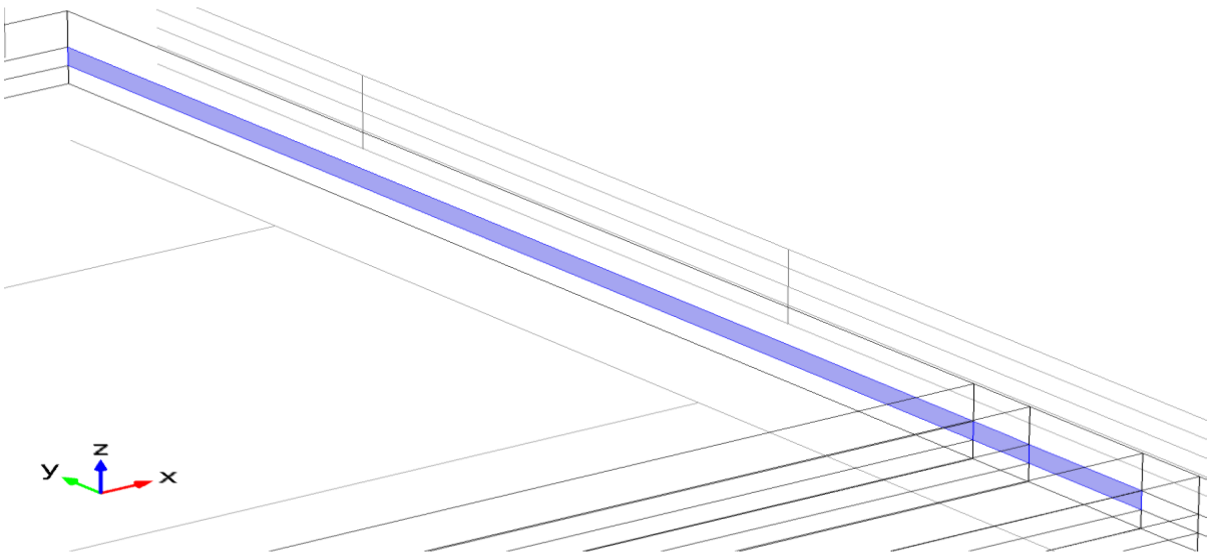


Figure 4.18: Selecting Symmetry 1 Axis in Geomertry

Selection

Geometric entity level	Boundary
Selection	Boundaries 114, 117, 120

Equations

$$n.u = 0 \tag{4.4}$$

Settings

Description	Value
Apply reaction terms on	All physics (symmetric)
Use weak constraints	Off
Constraint method	Elemental

Shape functions

Constraint	Constraint force	Shape function	Selection
-emi.nX*u-emi.nY*v-emi.nZ*w	test(-emi.nX*u-emi.nY*v-emi.nZ*w)	Lagrange (Quadratic)	Boundaries 114, 117, 120

(vi) Symmetry 2

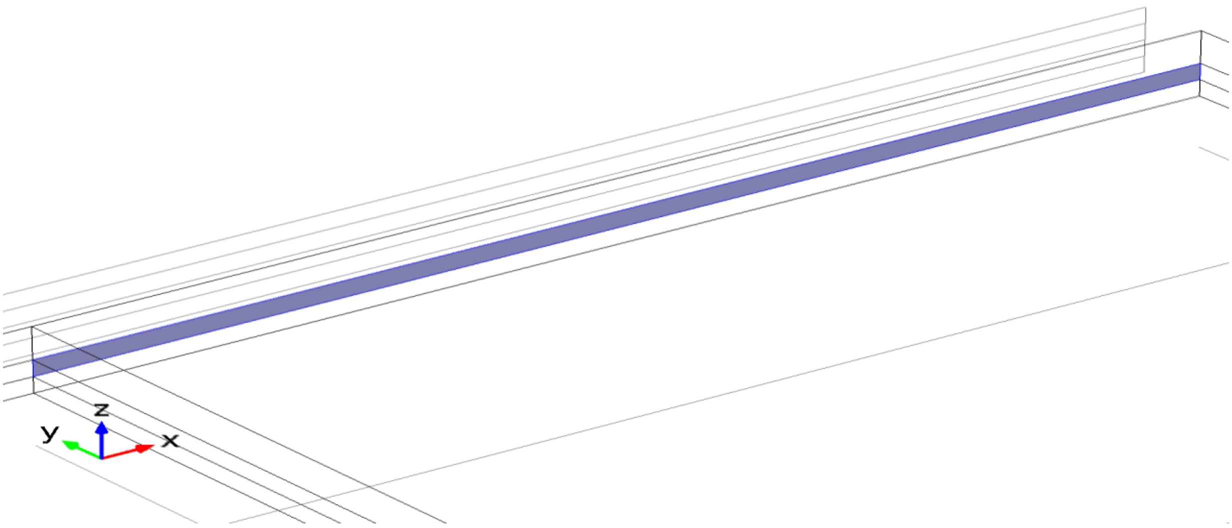


Figure 4.19: Selecting Symmetry 2

Selection

Geometric entity level	Boundary
Selection	Boundary 105

Equations

$$n.u = 0 \tag{4.5}$$

Settings

Description	Value
Apply reaction terms on	All physics (symmetric)
Use weak constraints	Off
Constraint method	Elemental

Shape functions

Constraint	Constraint force	Shape function	Selection
-emi.nX*u-emi.nY*v-emi.nZ*w	test(-emi.nX*u-emi.nY*v-emi.nZ*w)	Lagrange (Quadratic)	Boundary 105

(vi)Boundary Load 1

The load apply on the lower boundary of the surface,

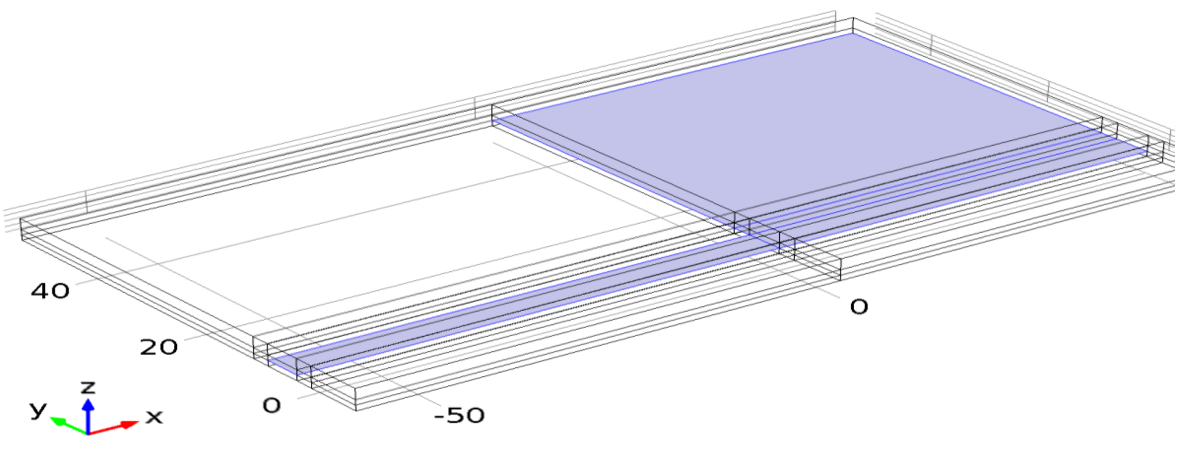


Figure 4.20: Setting up Boundary Load in COMSOL

Command on COMSOL

Selection

Geometric entity level	Boundary
Selection	Boundaries 26, 79, 89, 99

Equations

$$\sigma.n = F_A \quad (4.6)$$

Settings

Description	Value
Load	User defined
Load	{0, 0, contactpressure}
Load type	Load defined as force per unit area

Variables

Name	Expression	Unit	Description	Selection
emi.FperAreax	0	N/m^2	Load, x component	Boundaries 26, 79, 89, 99
emi.FperAreay	0	N/m^2	Load, y component	Boundaries 26, 79, 89, 99
emi.FperAreaz	contactpressure	N/m^2	Load, z component	Boundaries 26, 79, 89, 99

Weak expressions

Weak expression	Integration frame	Selection
contactpressure*test(w)	Material	Boundaries 26, 79, 89, 99

(vii) Prescribed Mesh Displacement 2

This is used to define the meshing displacement constrain in which direction the mesh is going to be compiled. So here is the description shown below in Figures 4.21 and 4.22.

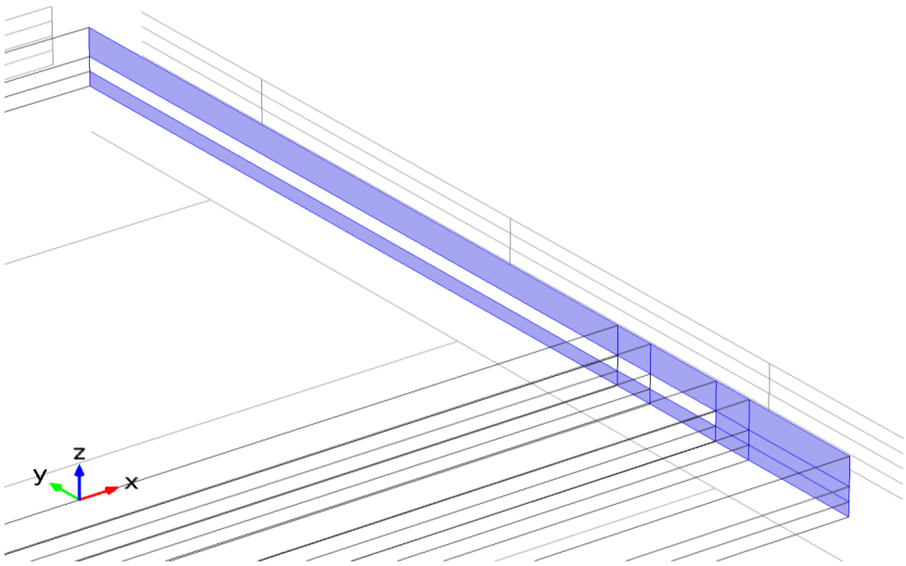


Figure 4.21:Prescribed Mesh Displacement 2 in COMSOL

Command in COMSOL

Selection

Geometric entity level	Boundary
Selection	Boundaries 107–113, 115–116, 118–119, 121

Settings

Description	Value
Prescribed # displacement	{On, Off, Off}
Prescribed mesh displacement	{0, 0, 0}
Use weak constraints	Off

Variables

Name	Expression	Unit	Description	Selection
emi.x_free	x	m	Coordinate, x component	Boundaries 107–113, 115–116, 118–119, 121
emi.y_free	y	m	Coordinate, y component	Boundaries 107–113, 115–116, 118–119, 121
emi.z_free	z	m	Coordinate, z component	Boundaries 107–113, 115–116, 118–119, 121

Shape functions

Constraint	Constraint force	Shape function	Selection
X-emi.x_free	test(-emi.x_free)	Lagrange (Quadratic)	Boundaries 107–113, 115–116, 118–119, 121
0	test(-emi.y_free)	Lagrange (Quadratic)	Boundaries 107–113, 115–116, 118–119, 121
0	test(-emi.z_free)	Lagrange (Quadratic)	Boundaries 107–113, 115–116, 118–119, 121

(viii) Prescribed Mesh Displacement 3

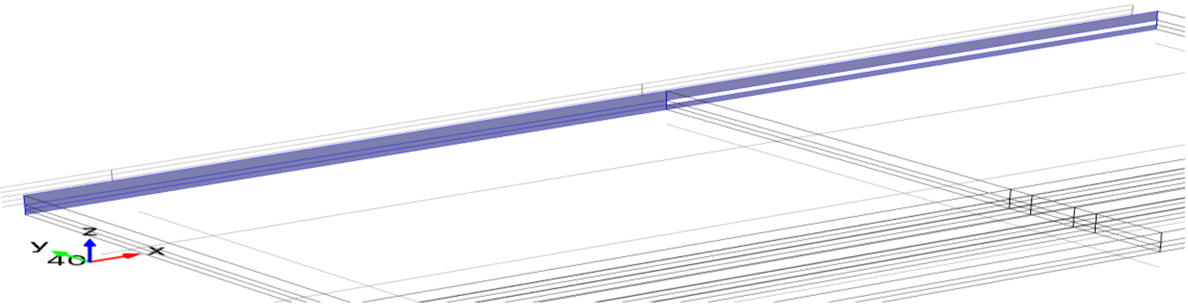


Figure 4.22: Prescribed Mesh Displacement 3

COMSOL command

Selection

Geometric entity level	Boundary
Selection	Boundaries 51–53, 104, 106

Settings

Description	Value
Prescribed # displacement	{Off, On, Off}
Prescribed mesh displacement	{0, 0, 0}
Use weak constraints	Off

4.8 GEOMETRICAL MESHING OF RF MEMBRANE

Meshing is defined as the small domain which is made by the the software to calculate the problem and it is same as the finite element methodology to solve the optimum solution, so here describing the meshing component and shown in Figures 4.23, 4.24 and 4.25.

(i) MESH 1

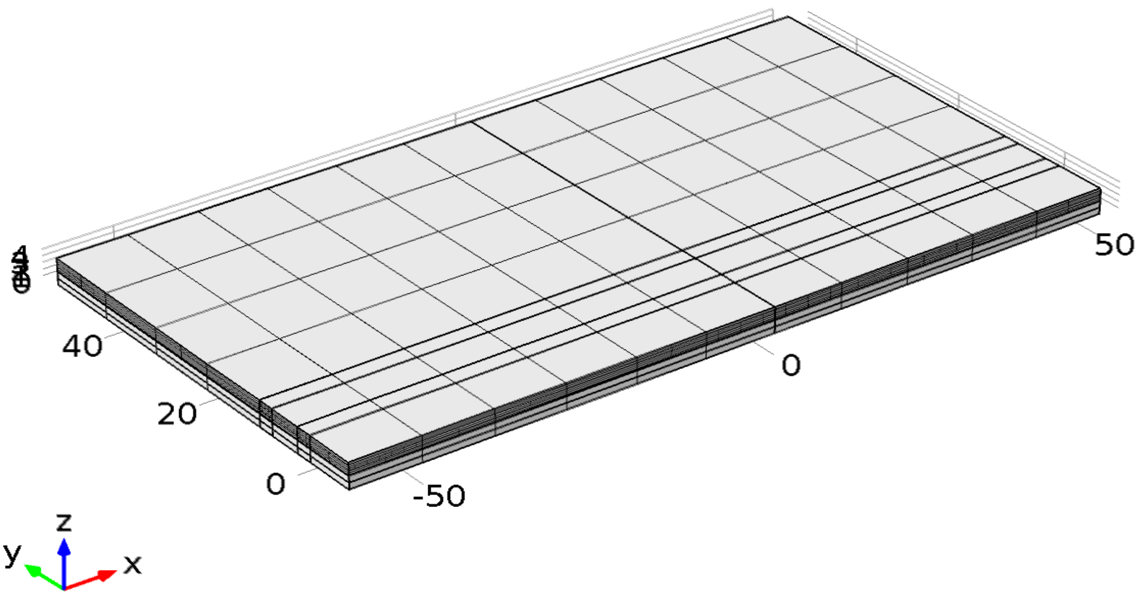


Figure 4.23: Setting up the Mesh 1

Size (size)

Property	Value
Minimum element quality	0.02963
Average element quality	0.06635
Hexahedral elements	880
Quadrilateral elements	1252
Edge elements	540
Vertex elements	72

Mesh statistics

Name	Value
Maximum element size	11
Minimum element size	1.98
Curvature factor	0.6
Resolution of narrow regions	0.5
Maximum element growth rate	1.5

Selection

Geometric entity level	Boundary
Selection	Boundaries 10, 20, 30, 40, 50, 63, 73, 83, 93, 103

(ii) Mapped 1

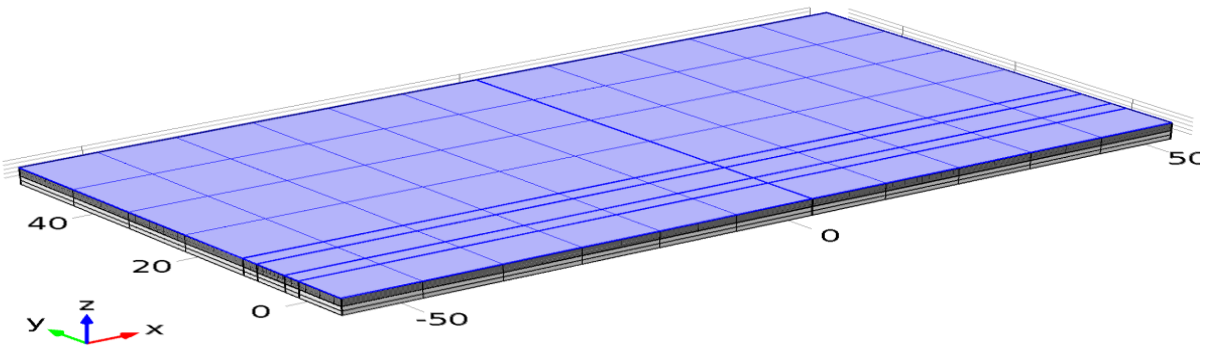


Figure 4.24: Setting up Mapped 1 in Comsol

Swept 1 (swe1)

Selection

Geometric entity level	Remaining

(iii) Distribution 1

Selection

Geometric entity level	Domain
Selection	Domains 3, 6, 9, 12, 15, 18, 21, 24, 27, 30

Settings

Name	Value
Number of elements	8

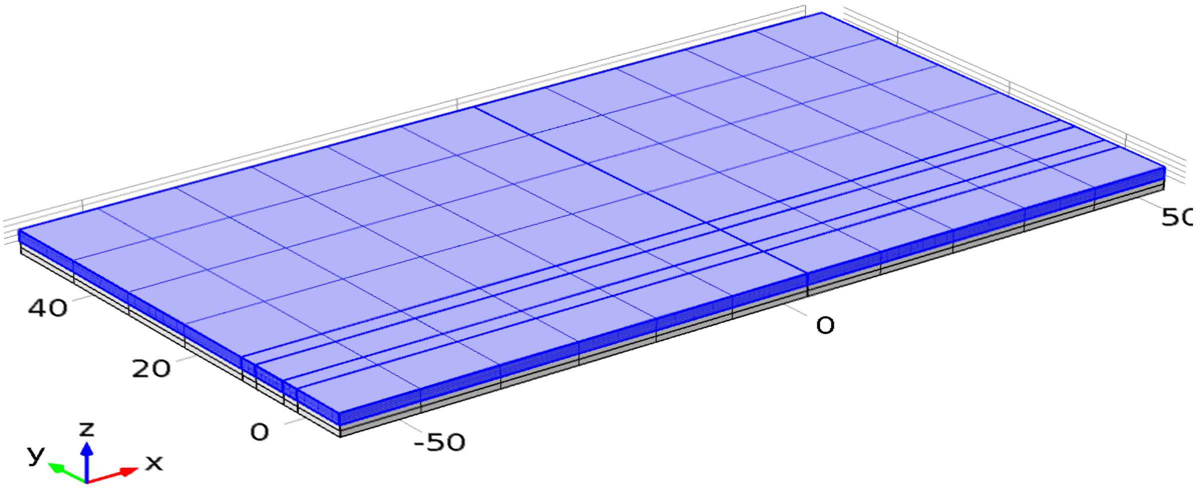


Figure 4.25: Distribution 1 on COMSOL

4.9 STUDY OF GEOMETRICAL CONSTRAINTS AND MESH SELECTIONS

It is the final step of COMSOL where the whole process is done with constraints and geometry the the study is going to rest in simulation so here the two studies are performed on this design and the first id the stationary study and the second is the time dependent study,

(i) Stationary

Study settings and commands

Property	Value
Include geometric nonlinearity	On

Physics and variables selection

Physics interface	Discretization
Electromechanics (emi)	physics

Mesh selection

Geometry	Mesh
Geometry 1 (geom1)	mesh1

(ii) Time Dependent

Study settings

Property	Value
Include geometric nonlinearity	On

Times	Unit
range(0,5e-7,5e-5)	s

Physics and variables selection

Physics interface	Discretization
Electromechanics (emi)	physics

Mesh selection

Geometry	Mesh
Geometry 1 (geom1)	mesh1

(iii) Solver Configurations

Solution 1

Compile Equations: Stationary (st1)

Study and step

Name	Value
Use study	Study 1

Name	Value
Use study step	Stationary

Dependent Variables 1 (v1)

General

Name	Value
Defined by study step	Stationary

Initial values of variables solved for

Name	Value
Solution	Zero

4.10 DESIGNING AND MODELING OF RF MEMS CAPACTIVE SWITCH

After modeling and simulating the switch in COMSOL 5.0 and Catia V5 is also used and the final part of the designing is shown in Figure 4.26,

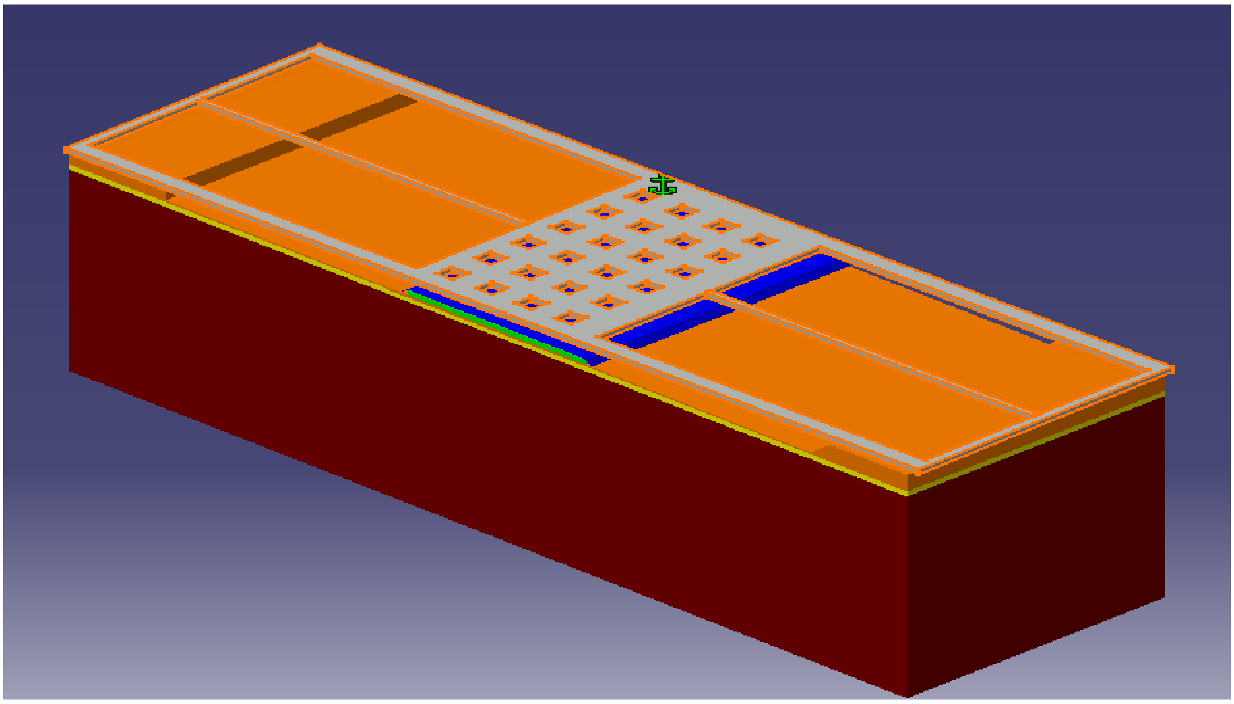


Figure 4.26: RF MEMS Capacitive Switch

Figure 4.26 shows the membrane in pink colour and the separator part of shows in yellow colour and CPW in orange and the substrate in black colour. Blue colour defines the di electric part of CPW.

4.11 ANALYSIS AND SIMULATION OF RF MEMS CAPACITIVE SWITCH

The membrane of RF Capacitive switch is simulated as one-fourth of its geometry. Its gives the sationary and time dependent solution in COMSOL 5.0 and the stationary interface calculates von Mises stress and time dependent interface determines Eigen's frequency and displacement of the membrane with the frequency.

4.11.1 Von Mises Stress Computation

A material is start yielding when its von Mises stress touches a critical value known as the yield strength σ_y. Von Mises stress is calculated and simulated as yielding of materials under any loading conditions from results of simple uniaxial tensile tests. Von Mises stress satisfies the property that two stress states with equal distortion energy have equal stress quantified values. Figure 4.27 shows the calculated value of von Mises stress varies between Max. 1.09×10^6 N/m^2 to Min 1.69×10^4 N/m^2.

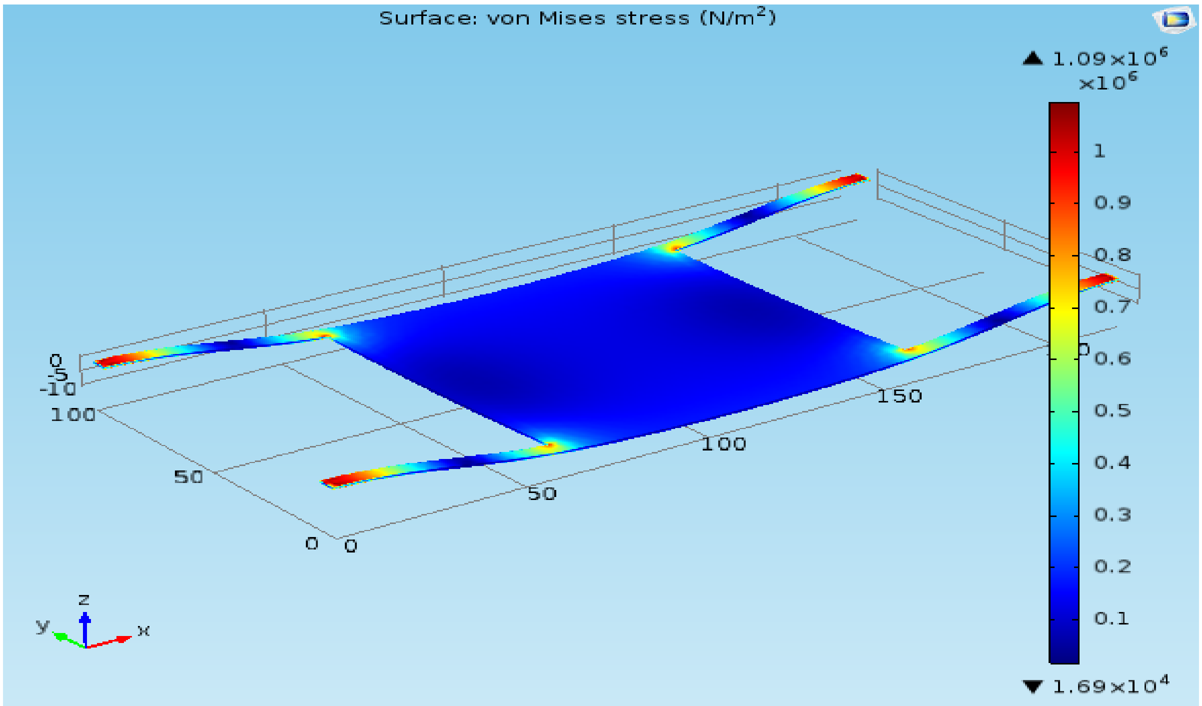


Figure 4.27: Computation and Simulation of von Mises Stress of Membrane

Also calculating the von Mises stress and applying holes in diameter 2µm. As the result displayed in Figure 4.28, the stress computed is less compared to stress depicted in Figure 4.27 which is 8.97×10^5 N/m^2 (Max) to 3549 N/m^2(Min).

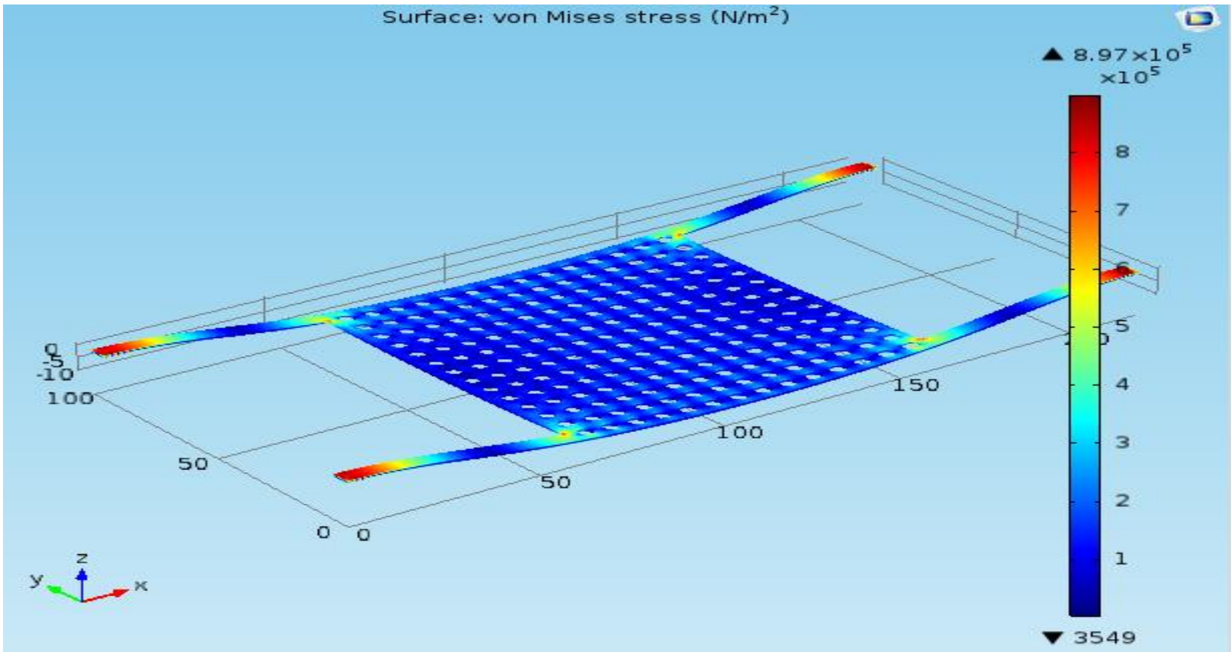


Figure 4.28: Calculation and Simulation of von Mises Stress of Membrane with Holes

4.11.2 Displacement of membrane

The displacement of the membrane bridge is calculated in COMSOL 5.0 Software and Eigen's frequency is also calculated during the simulation process. After calculation of the displacement of membrane, it is found to be as 1.89 µm maximum displacement.

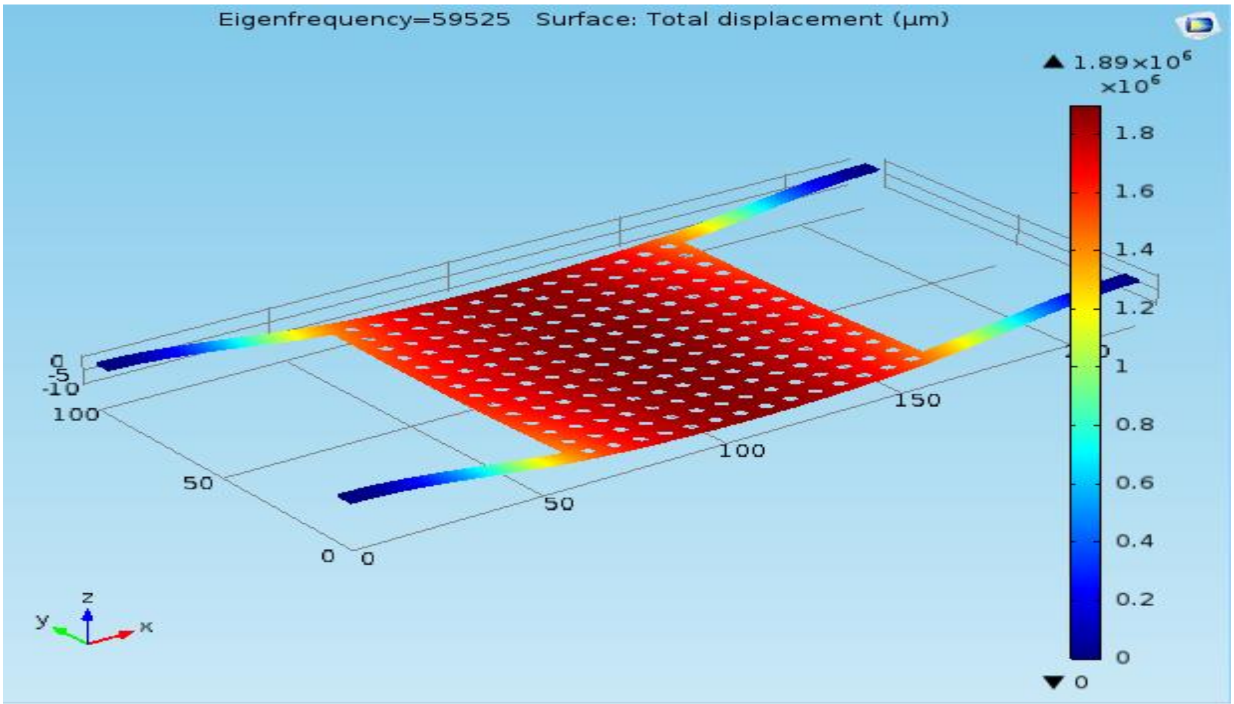


Figure 4.29: Eigen Frequency and Maximum Displacement of Membrane

Figure 4.29 depicts the maximum displacement is the middle side of the membrane which is further actuated on the CPW for electrostatic actuation. Figure 4.29 displays Eigen's frequency as well as the displacement of membrane. The optimum deflection is successfully obtained is to be applied at the electrostatic mechanism and therefore, it is hardly tough to apply the electroststic such a low voltage and further, it is possible to make a interface to software that can be simulated on COMSOL 5.0. The step by step of the simulation process of electrostatic functions is shown in Figure 4.30.

4.12 ELECTROMECHANISM INTERFACE

This interface finds the electrostatic calculation and simulation in time dependent and frequency domain as well as so generates the result simulates in COMSOL. After result analysis, the modules of the Multi-Physics interface finds the results in terms of displacement, potential, and contact force which are shown and described in below sub-sections:-

4.12.1 Displacement

Figure 4.30 shows the displacement of the membrane with 1 to 5 µs time interval due to voltage,

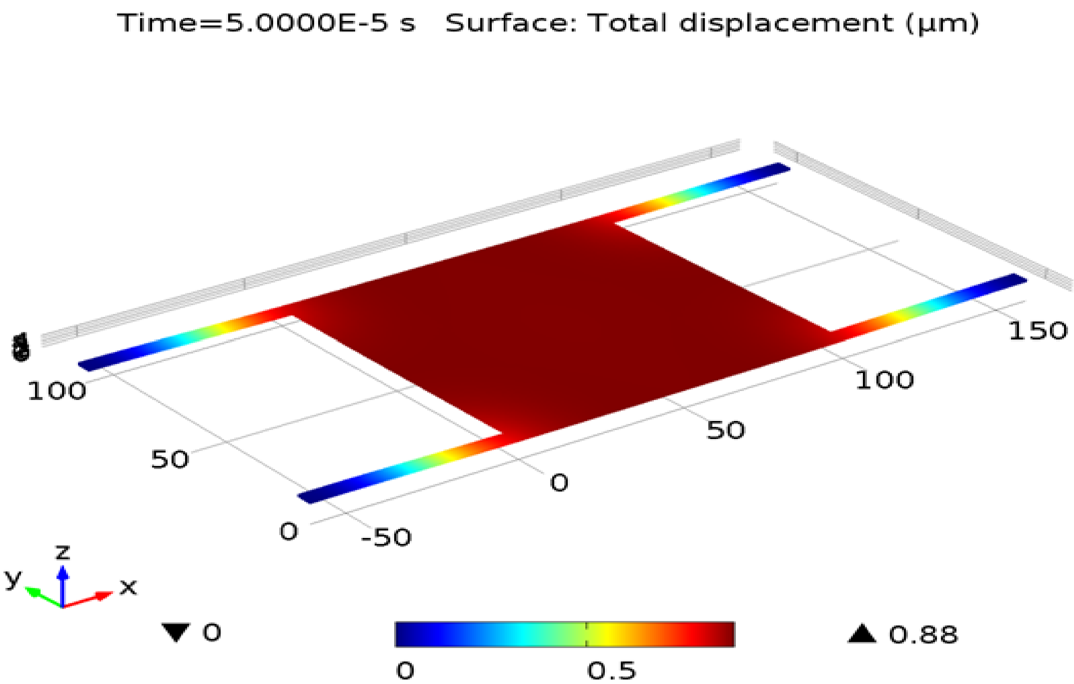


Figure 4.30: Time=5.0000µs Surface: Total Displacement (µm)

Figure 4.30 shows the dispalecment of membrane is 0.88 µm that is calculated on 5V and this is the pependicular deflection of membrane.

4.12.2 Potential

Figure 4.31 shows the voltage distribution on membrane after application of 1mV to 5V in a time interval of 1 to 5µs and calculates the voltage variation and distribution over membrane and depicts the effect of voltage variation over the membrane in below shown Figure.

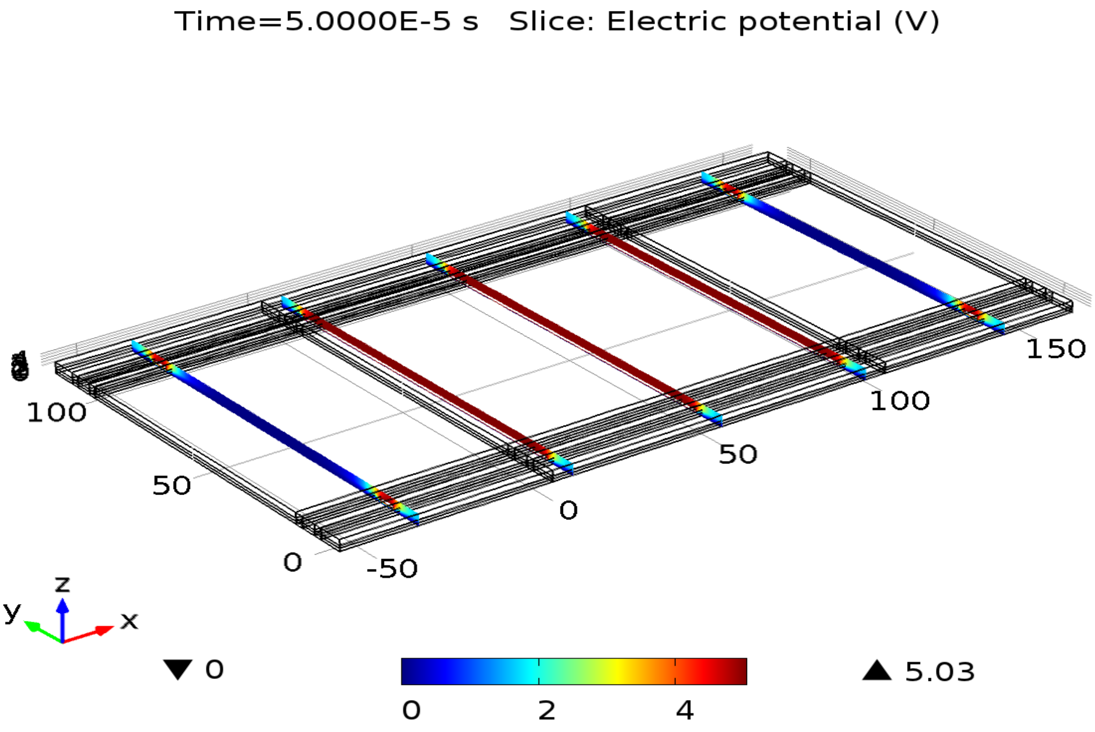


Figure 4.31: Time=5.0000 µs Slice: Electric potential (V)

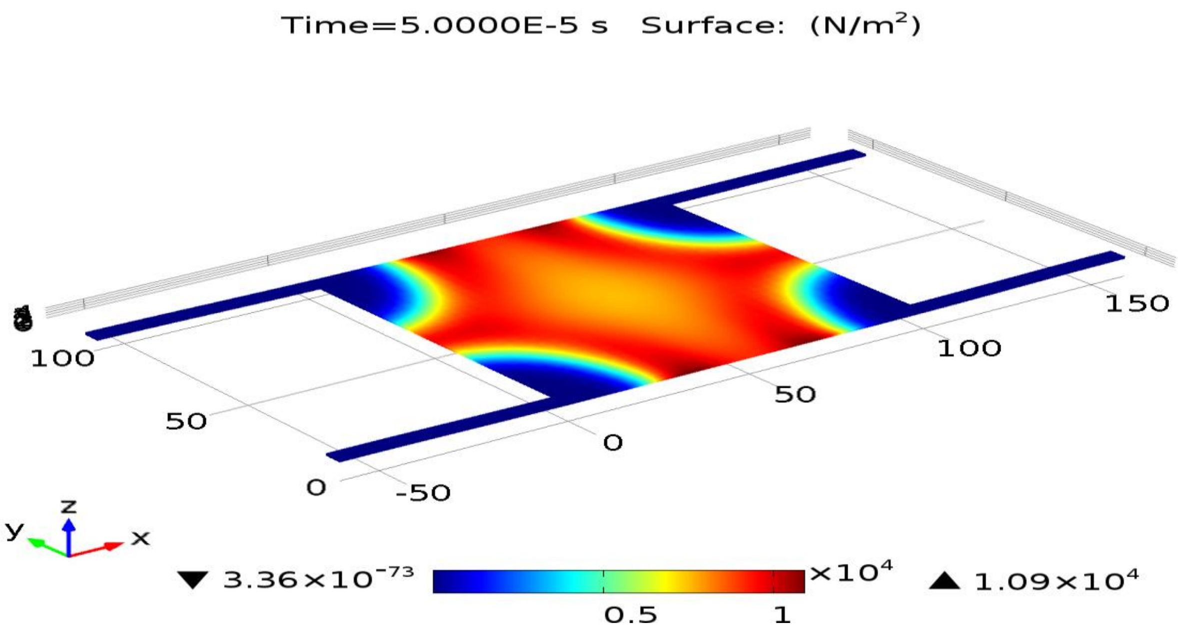


Figure 4.32: Contact Force after 5µs

4.12.3 Contact Force

The contact force is the force acting on the surface of the membrane due to the voltage application so that the perpendicular deflection occurs as the effect of the whole simulation process. The contact force is calculated is $1.09x10^4$ N/m^2 as shown in Figure 4.32.

4.13 FATIGUE EVALUATION AND VALIDATION OF THE MODEL

In the context of results analysis and simulation process, the fatigue evaluation is performed, the determined von Mises stress is 1.09GPa and the displacement of 0.88µm gives the optimum results to find the fatigue damage of the device. The normal fatigue strength of aluminium from the conventional and conceptual results is 131MPa and the proposed device gives the value of 1.09 MPa of stress in 1 Pa boundary load in cyclic time interval of 5µs. Hence, the determined value validates the fatigue resistant of the device and its calculation and simulation aspects. The simulation test is performed on Multi-User MEMS Process (MUMPS) and Parellel Direct Solver (PARDISO) in COMSOL 5.0 software interface which validates from two different modules.The two generated graphs are shown during the simulation in Figures 4.33 and 4.44.

(i) Time Displacment Curve

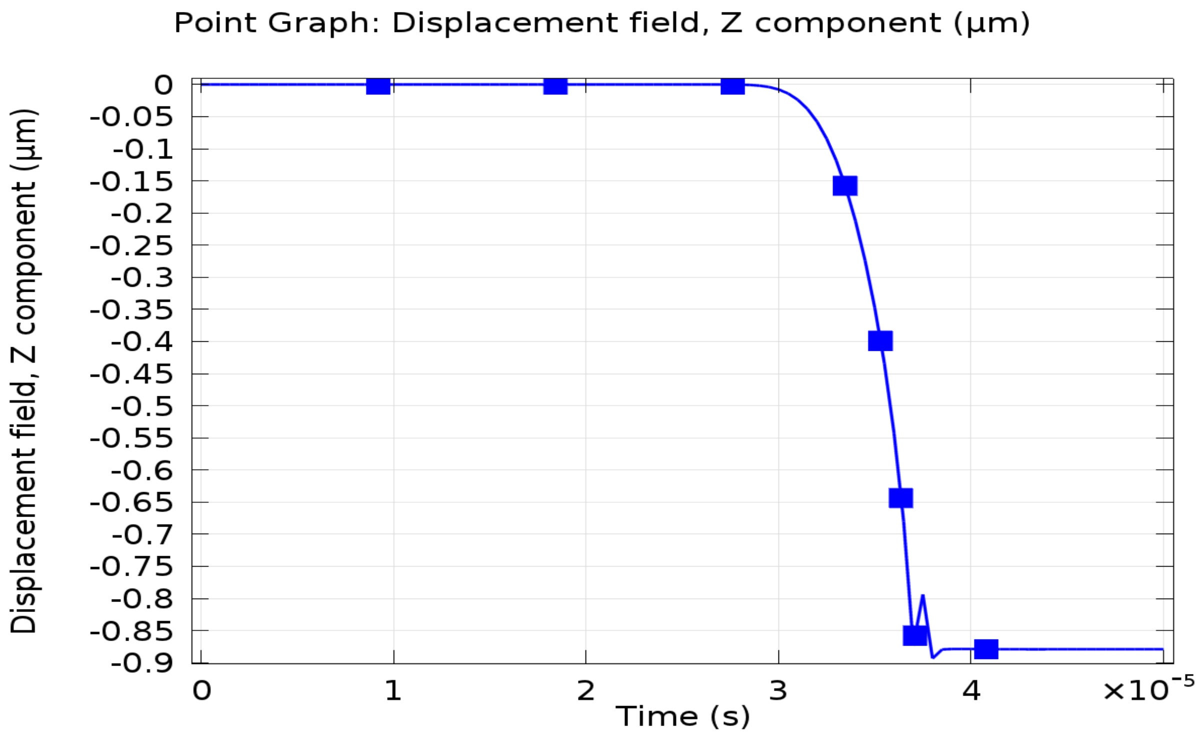


Figure 4.33: Time-Displacement Diagram

Figure 4.33 shows the time displacement curve when the voltage is applied, the membrane is deflected maximum at 0.88µm in 3µs seconds.

(ii) Capacitance

Capacitance gives the attraction force between the membrane and the dielectric. More the capacitance more attraction force is formed and the proposed device is achived 8.4 pf of the capacitance which is more than enough to attract the membrane as per MUMPS module. The determined value of capacitance is near the acceptance and also, it is also calculated from COMSOL interface and the generated graph is show in Figure 4.34, in which the capacitance is found as 8.9 pF.

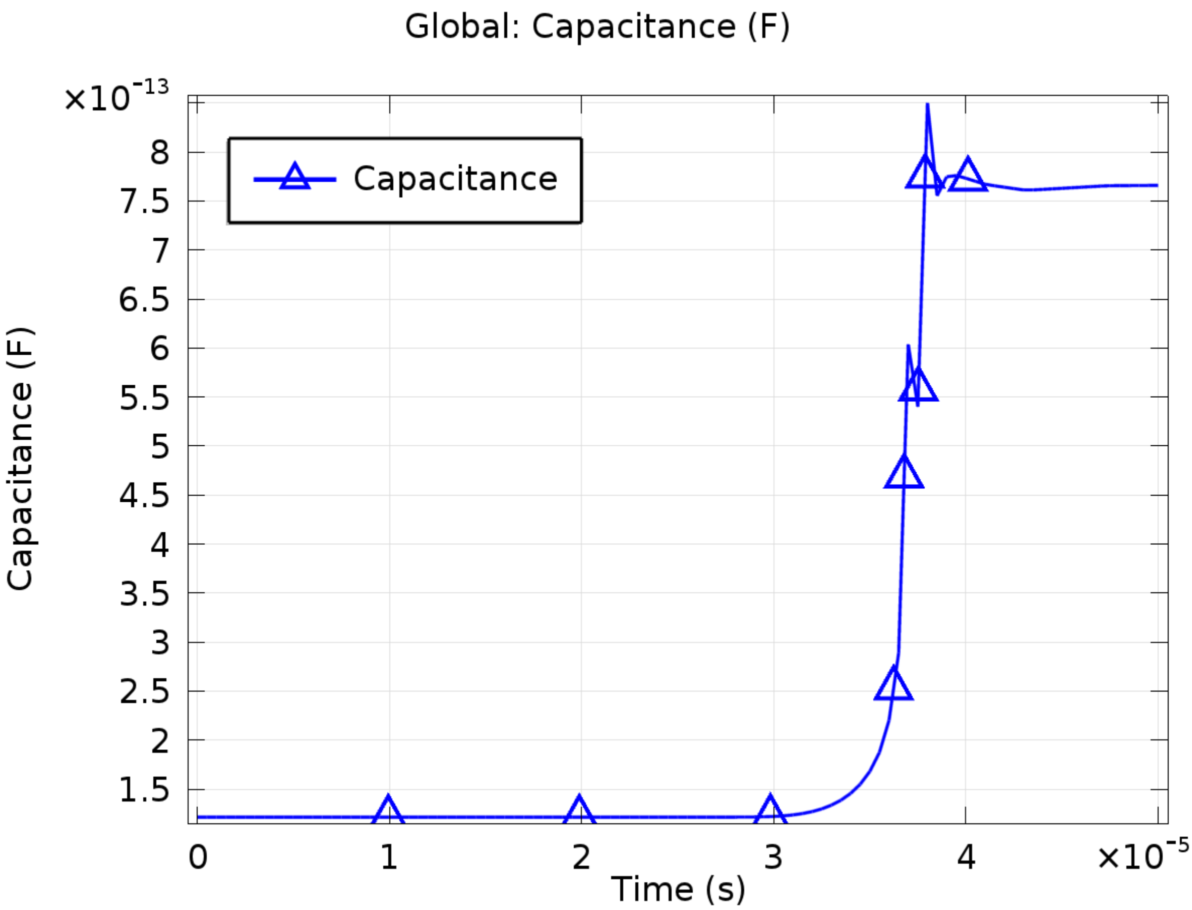


Figure 4.34: Time-Capacitance Graph

CHAPTER 5: CONCLUSION AND FUTURE SCOPE OF WORK

5.1 CONCLUSION

A novel configuration of RF MEMS capacitance switch with hybrid switch configuration are studied and analyzed in the present research work. It is analytical model and derived to facilitate comparisons. Firstly, its Finite Element Method is created and simulated in COMSOL 5.0 to show its better static and transient performance over the others. Even though the moving beams in this design are of proportionate size and torsional stiffness and dynamic changes to the beams can be made to meet a specific applications. Furthermore, this concept can be easily extended to create a less complex design with hybrid flexures and use of point contacts over the contact areas mainly at the transmission line. The use of fillets at the edges of flexures helps to reduce the stress gradients by a great extent and hence must be applied for meanders designs to help the reduction of stresses in previously designed RF MEMS switches. In this dissertation, the design and testing of RF MEMS contact switch with hybrid flexures is presented. Analytic stress gradient models are developed and resulted in predictions that agreed with measured graphical values. Overall, the results analysis show increased lifetimes at the expense of a small increase of geometrical values for RF MEMS devices. The present design has advantages over the existing design of capacitive switches and the conclusions drawn from the results are mentioned as follows:

1. The present design declares that the stiction of the membrane is positively less compared to the existing design because of holes.
2. The determined and simulated stiffness of membrane is less compared to the previous design due to the thickness of 1µm of membrane.
3. The present design focuses on the calculation of the von Mises stress and displacement for membrane due to potential and also, Eigen's frequency of membrane because of RF MEMS applications.
4. After calculating the displacement and von Mises, it shows the maximum displacement of the membrane is 0.88 µm which is feasible and the voltage is applied on the membrane is varies between 1µV to 5V in simulation and found that after 4.5µs it is reached the dielectric and the signal transmit through the transmision line.
5. The von Mises stress computed is 1.09 MPa which is less compared to the previous device of membrane and with hole it was found 40 MPa.

5.2 RECOMMENDATIONS

1. COMSOL 5.0 Multiphysics software gives the better environment of the modeling of switch and its interface is easier to understand the tool is given by the software is easily available and also the material tree gives good help to find suitable material to attach.
2. The present capacitive switch gives the frequency of 5MHz to 5GHz application in RF devices.
3. It is recommended the calculation of the von Mises and displacement for membrane gives the result in low voltage and the device is more relevant for fabrication.
4. The present research work would suggest the implementation of statistical software like COMSOL 5.0 and CATIA V5 modules for the calculation of von Mises stress and displacement and contact force analysis part is done by the Comsol and the design is done by the Catia V5 with their best fitted models.
5. The present research work would optimize the fatigue with using substrate BN(Ca) grade and the design is finalized by removing the sharp egdes.

5.3 FUTURE SCOPE OF WORK

This section addresses the important work that is still required in RF MEMS devices. It seems that a lot research has been consummated in the past 7–8 years, but it subdues into a ‘‘fine-tuning’’ mode. But, this also takes a lot of effort, and every person who has done research and development sees that most of the exercises are expended when one tries to take a 90% mature technology to a 97% maturity level. Vital, it would understand RF MEMS devices from electrical and mechanical viewpoint, even though more work is still required on the dynamic analysis of MEMS switches. Topics of future work contain reliability, packaging and yield of MEMS switches, as well as the insertion of low-cost MEMS components into reconfigurable systems switches.

1. Medium- to high-power (0.05–5W) metal-to-metal contact switches, and high-power (0.5–5W) capacitive contact switches are to be required. This may be accomplished at the expense of size and switching speed of the device.
2. MEMS switches with a switching time of 100–200 nano seconds and an actuation voltage of 30–50 V should be established.
3. Higher fabrication yield is to be required for the construction of complicated phase shifter and switching networks. A fabrication yield of 96% is simply not acceptable in an 8- to 16-switch circuit.

4. Low-cost, wafer-scale, high-yield hermetic packaging techniques are essential for low-cost applications. There is currently a lot of work in this area, but most is proprietary.

5. The reliability studies of MEMS switches should continue at an accelerated pace. The study of metal contacts, dielectric layers, dielectric formation, and so on, and why a switch fails is the only way to allow MEMS switches to be taken to >100 billion cycles.

7. Reliability studies of RF MEMS switches under different temperature and radiation effects are also urgently required. Other areas include reliability versus power level, hot and cold switching, and long-term power application. Also, it is important to study the reliability under nonthermetic conditions to determine the gases that adversely affect the operation of RF MEMS switches.

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