LOW VOLTAGE MOBILE COMPATIBLE RF MEMS SWITCH FOR RECONFIGURABLE MICROSTRIP ANTENNA

Moataz Mohamed Medhat
Moez Mahmoud El-Massry

Under the Supervision of
Dr. Hassan Mostafa

Electronics and Communications Engineering

Faculty of Engineering, Cairo University
Giza, Egypt

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List of Symbols and Abbreviations

MEMS	Micro Electro-Mechanical Systems
RF	Radio Frequency
IL	Insertion Loss
FEA	Finite Element Analysis

Acknowledgments

This dissertation does not only hold the results of the year work, but also reflects the relationships with many generous and stimulating people. This is the time where we have the opportunity to present our appreciation to all of them.

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Abstract

The purpose of the project is to utilize the MEMS Technology advances in the RF field, in order to design a low voltage RF MEMS Switch to be integrated in a microstrip reconfigurable antenna that would save area, power and cost of communication devices. Also the ability to reduce the cost of updating hardware systems (i.e. installed in a mobile phone) each time a new technology evolve (i.e. LTE). Through this thesis we discuss RF MEMS Switch design and propose two RF MEMS Switches (electrostatic actuated metal to metal contact type).

Chapter 1: **Introduction**

In communication systems, a concept called Software Defined Radio (SDR) is adopted to implement a certain function using software algorithms running on a PC or an embedded system. Using SDR systems would save area, power and cost of communication devices. Also the ability to reduce the cost of updating hardware systems (i.e. installed in a mobile phone) each time a new technology evolve like LTE. SDR different Implementations require switching between standards. Thus a reconfigurable antenna is needed to switch between different standards centre frequency and bandwidth.[1]

A typical reconfigurable microstrip antenna (as shown in Figure 1) would require a RF switch that is near to the ideal switch performance (Open Circuit OC & Short Circuit SC modes), high switching speed (typically equal to standard frame time), almost infinite life cycle, uses 3.3 volt to operate and low power (to be compatible with mobile phones).

The latter requirements specially OC and SC constrain make it impossible for the commercial solid-state devices, such as PIN diodes or FET switches to fit this application.[2]

The importance and size of the RF market have led the researchers and industry to search for alternative ways to enhance RF devices performance.[2] And so the RF Micro-Electro-Mechanical Systems (MEMS) were introduced and resulted in low insertion loss, high isolation, low power consumption (~a few μ-watts) much lower intermodulation distortion, small footprints, low cost and lightweight.[3]

In this thesis we introduce two switches that are compatible with the mobile phone reconfigurable microstrip antenna application and resulted in excellent RF performance.

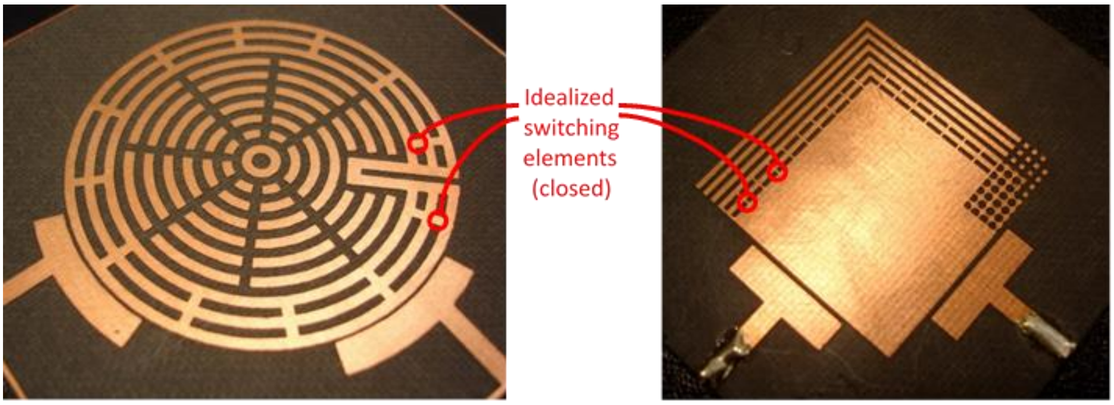

Figure 1: Reconfigurable Microstrip Antenna

This thesis is organized as follows: Survey in Chapter 2, MEMS RF Switch in Chapter 3, MEMS RF Switches Library in Chapter 4, Required RF Switch Specifications in Chapter 5, First Proposed Design in Chapter 6, Second Proposed Design in Chapter 7, and finally Conclusion in Chapter 8.

Chapter 2: **Survey**

Recent years have witnessed a great rising in the MEMS market, with large, increasing volumes driven by consistent smart phone shipment growth.

The market for smart phones applications is reaching saturation, which means MEMS markets are growing slower than its growth in the preceding years. Today, the compound annual growth rate (CAGR) from 2015 to 2021 for the value of MEMS markets will go to 8.9%, moving from \$11.9B to \$20B. (Figure 2).

The consumer market is challenging MEMS manufacturers. Although volumes are still increasing, this market is becoming highly competitive. Using sensors such as MEMS microphones, inertial, pressure and gas sensors in mobile devices is increasing, but these devices have very low margins today. Meanwhile, end users are giving their suppliers a hard time as the customer loyalty to manufacturer decreases, shifting from one device maker to another. Moreover, no large volume markets being a short- term growth driver for MEMS:

Wearable electronics applications look very promising as part of the consumer industry, but there are some rich seams in other markets Industrial, medical and automotive applications still offer pockets of growth and profitability.

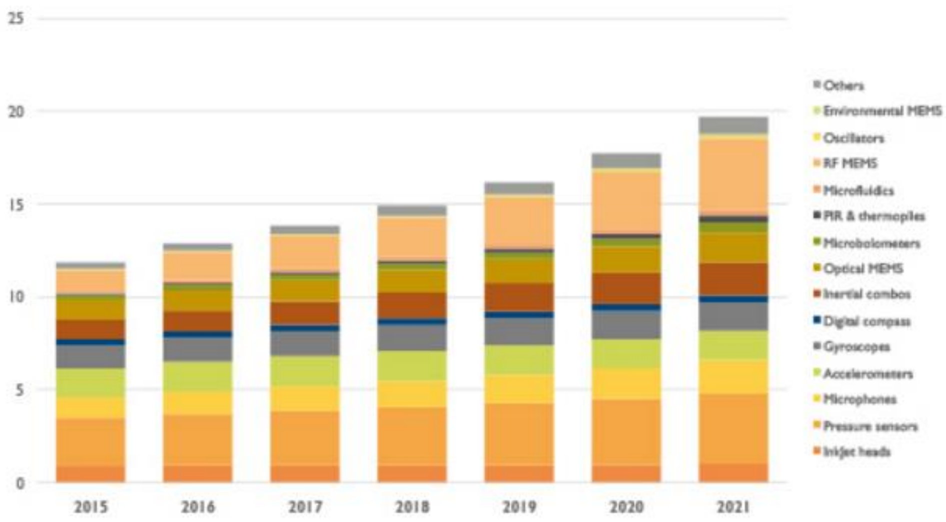

Figure 2. 2015-2021 MEMS market forecast

The car industry seems not satisfied with the number of sensors in it, with 20 MEMS devices per car on average today, and autonomous cars might offer more possibilities for MEMS technologies. New opportunities in medical come with long-term developments that are finding the market today.

Industrial and defense markets also provide growing opportunities for high-end and high-margin devices such as inertial and pressure sensors.[4]

Chapter 3: MEMS RF Switch

3.1 RF Switch

3.1.1 Definition

RF switch is a device to route high frequency signal through transmission paths.

Before discussing different RF switch specifications, it is first important to understand the difference between how signals propagate in DC circuits versus RF systems. In DC circuits or circuits where the propagating signal has low frequencies, the voltage of the signal at different points on a cable in the signal path varies minimally. This is not so in the case of RF or high-frequency signals where wavelength of the signal is considerably small in comparison to the length of the cable allowing multiple cycles of the signal to propagate through the cable at the same time.

Consider an example where two waves (signals) of different frequencies are made to propagate through a 1 m coaxial cable. The frequency of the first signal is 1 MHz while that of the second signal is 1 GHz. To calculate their wavelengths, we will use the following formula:

$$\lambda = \frac{C}{f} = \frac{3 * 10^8}{f}$$

In the above formula, λ is the wavelength of the signal, f is its frequency,

Then for

$$\lambda_1 = 0.66 * \frac{3 * 10^8}{1 * 10^6} m = 198\, m$$

Signal 1 where f = 1 MHz:

In the case of Signal 1, the length of the coaxial cable is considerably small in comparison to the wavelength of the signal propagating through it. Therefore, as can be seen in Figure 3, the variation in potential of the signal at different points in the cable is negligible.

For Signal 2 where f = 1 GHz:

$$\lambda_2 = 0.66 * \frac{3 * 10^8}{1 * 10^9} m = 0.198\, m$$

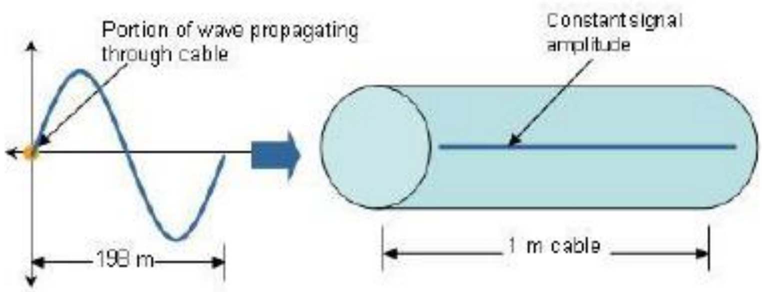

Figure 3. A 1 MHz Sine Wave Propagating through a 1 m Coaxial Cable

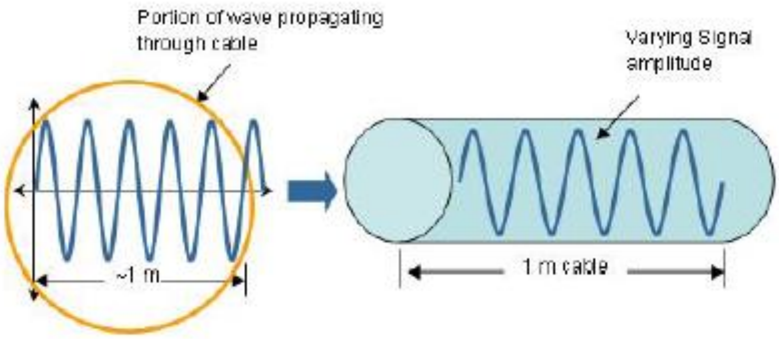

Figure 4. A 1 GHz Sine Wave Propagating through a 1 m Coaxial Cable

In the case of Signal 2, the length of the coaxial cable is much larger (almost 5X) than the wavelength of the signal propagating through it. Therefore, at any given time, multiple cycles of the signal will travel through the cable simultaneously as shown in Figure 4. Because of their small wavelengths, high-frequency signals travel through cables in waves. Such signals therefore suffer reflections and power loss when traveling between varying media (wave theory). In the case of electrical circuits, this variation in medium takes place when the signal (wave) is made to pass through system components that have varying characteristic impedances. Therefore, to minimize reflections and power loss, RF systems must be constructed using suitable components with matched impedances. As a rule of thumb, signal degradation due to power loss and reflections that occur in the transmission line become significant once the length of the cable exceeds 0.01 of the wavelength of the signal it is being used to route.

3.1.2 Characterization

Some of the main specifications for characterizing an RF switch is:

- Operating Voltage

  The supply voltage at which the switch operates properly.

- Power Consumption

  The power needed to be supplied for the switch and it is needed to be low as possible.

- Durability

  The number of cycles the switch operates before it breaks down.

- Insertion Loss

  The loss of electric power spread from one terminal to another in a high frequency circuit which consists of two terminal-pair networks after the circuit has been closed.

- Isolation

  The ratio between the input power and the reflected power at one terminal in the high frequency circuit.

- Switching Time

  The time needed for the switch to operate properly.

- Power Handling

  The maximum signal power the switch can operate at without being damaged.

- Frequency range

  The set of frequencies of the signal the switch can operate at.

3.2 MEMS RF Switch

3.2.1 Basic Idea of Operation

MEMS is written as “Micro Electro Mechanical Systems”, it is a technology of very small devices that are fabricated by semiconductor device fabrication technologies. Some micro scale mechanical components, sensors, actuators or electrical circuits are integrated on one silicon substrate, glass substrate, and organic substrate and so on.

For simplicity in clarifying the basic concept of MEMS RF switch, we will discuss Metal to metal series switch and different configurations differ slightly with the same basics as will be discussed later.

In this case, we consider two isolated transmission lines (Ports) RF IN and RF OUT and a free moving cantilever in the Z-direction anchored in the substrate from the other side as shown in Figure 5.

The anchor is the part of the structure that is fixed to the substrate and the cantilever is free from the other end.

In the normal operation the cantilever made of metal is in the up state and the two lines are isolated, for the switch to operate the cantilever is electrostatically actuated and pulled down causing contact between the cantilever and each line leading to having RF path so as for the signal to flow.

A voltage difference is applied between electrode and the cantilever causing electrostatic force that pulls down the cantilever and that type of actuation is called Electrostatic actuation.

3.2.2 Comparison of MEMS Switches with Gaas Pin Diode and Transistor Switches

It is hard to make an accurate comparison over a wide range of RF power levels since the size of diode and transistor switches can be easily increased for high power applications. This, in turn, has a substantial effect on the switch isolation, insertion loss, switching speed, and power consumption. Still, it is evident that MEMS switches, with their extremely low up-state capacitance (series switches) and their very high capacitance ratio (capacitance contact switches), offer a far superior

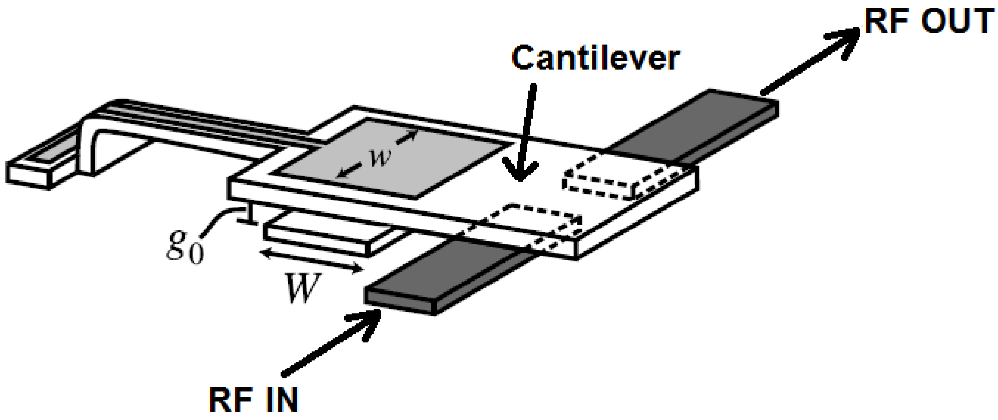

Figure 5. Simple series metal to metal contact MEMS RF switch

performance compared to solid-state switches for low to medium power applications as shown in Figure 6.[3]

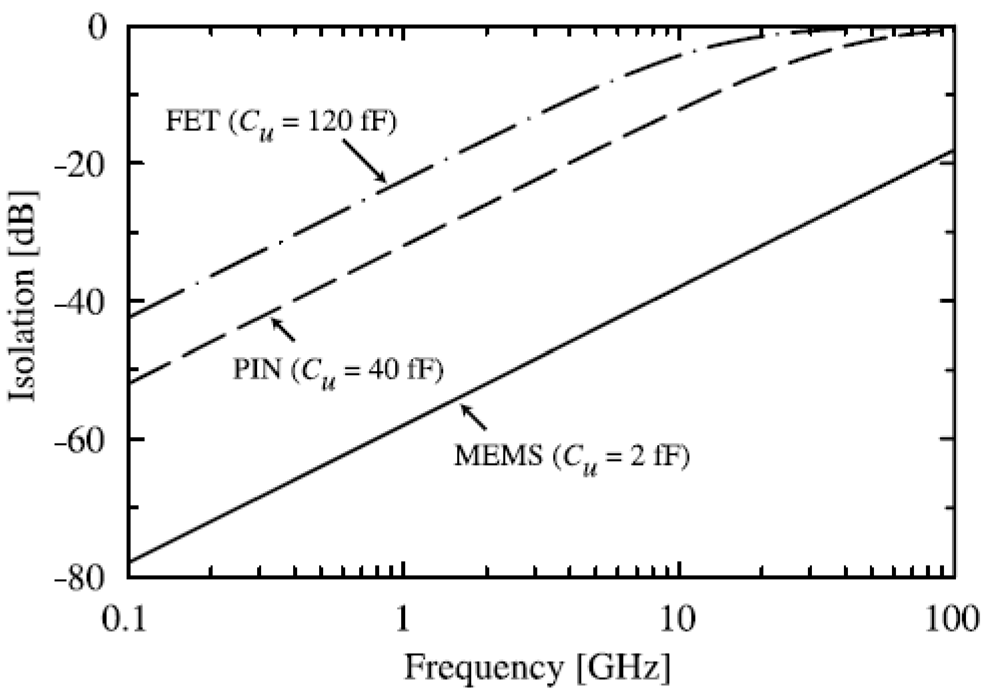

Figure 6. Simulated isolation of MEMS, PIN, and FET series switches.

3.2.3 Different configurations of RF MEMS Switch

RF MEMS switch can be classified into four different classifications:

1. Type of actuation
2. Movement
3. Contact type
4. Circuit configuration

3.2.3.1 Type of actuation

3.2.3.1.1 Electrostatic actuation

It relies on the attractive force between two conductive plates which is caused by an applied voltage.

3.2.3.1.2 Magnetic

Electrical current in a conductive element that is located within a magnetic field gives rise to an electromagnetic force (called the Lorentz force) in a direction perpendicular to the current and magnetic field

This force is proportional to the current, magnetic flux density, and length of the element

3.2.3.1.3 Piezoelectric actuation

Piezoelectricity is the ability of some crystals to create mechanical stress, or motion by expanding or contracting in response to an applied voltage

Piezoelectric actuation can provide significantly large forces, especially if thick piezoelectric films are used

3.2.3.1.4 Thermal actuation

The difference in the thermal expansion coefficients between two joined layers of dissimilar materials cause bending with temperature

One layer expands more than the other as temperature increases and that results in stresses at the interface and consequently bending of the stack

The amount of bending depends on the difference in coefficients of thermal expansion and absolute temperature.

3.2.3.2 Movement

3.2.3.2.1 Vertical

Typically results in small size devices

3.2.3.2.2 Lateral

Typically results in large size devices

3.2.3.3 Contact type

3.2.3.3.1 Metal-to-Metal

Used in relatively low frequencies.

3.2.3.3.2 Capacitive

Used in relatively high frequencies.

3.2.3.4 Circuit configuration

3.2.3.4.1 Series

DC-50 GHz with metal-to-metal contact and low up-state capacitance.

10–50 GHz with capacitive contact and low up-state capacitance.

3.2.3.4.2 Shunt

DC-60 GHz with metal-to-metal contact and low inductance to ground.

10–200 GHz with capacitive contact and low inductance to ground. [3]

3.3 Challenges and tradeoffs

In this section we discuss certain switches parameters, how to enhance a certain parameter, how this increase affect other parameters (tradeoffs) and what challenges that face the switches performance at the microscale.

3.3.1 Actuation Voltage

Typically electrostatic actuated switches need tens of volts to operate; 40-120 V. Following we discuss what dominates the actuation voltage value.

We can deduce that the pull-down voltage "V_p" of a typical switch is as follows (as proved in [3] Chapter 2, Section 2.6):

$$V_p = \sqrt{\frac{8k}{27\epsilon_0 W w} g_0^3}$$

Where k is the switch beam stiffness, g_0 is the zero-bias bridge height, ϵ_0 is the air permittivity, W is the width of the pull-down electrode and w is the width of the beam (Cantilever or Membrane).

From the above equation we can deduce that we have 4 parameters to tune in order to get the required (i.e. reduce it in most cases) pull in voltage, introducing 4 cases:

3.3.1.1 Case 1 "Tuning g_0"

Decreasing g_0 in order to reduce voltage is a fine approach, but at very small g_0 we must take consideration of:

1- Vibrations that may actuate the switch without any applied voltage (as small variations in i.e. cantilever height may result in contact)
2- In capacitive type switches this would result in small capacitance ratio between the up and down state

3.3.1.2 Case 2 "Tuning W"

As we increase W, thus increasing the intersection area between the electrode and the beam leading to decreasing the pull in voltage. The limitations of increasing W:

1- Increasing the intersected area, increase the stiction forces (electrostatic charging) effect, as it will discuss later in this section.

2- Note that W is increased on through the Cantilever or membrane area (increasing it beyond that is meaningless in most cases), so for a limited area as W is increased, it decreases the pull in voltage, till the maximum of W through the cantilever area is reached, then it's needed to increase the cantilever length, thus increasing area, which sometimes could be a limitation.

3.3.1.3 Case 3 "Tuning w"

For the first look it may be considered that tuning w, changes the pull in voltage, but that's not true as k varies linearly with w (see Equ. 2.16 in chapter 2 in [3]), and so the pull in voltage is independent on w.

3.3.1.4 Case 4 "Tuning k"

K is reduced either through increasing beam length, decreasing beam thickness or decreasing residual stress (see Equ. 2.16 in chapter 2 in [3]). But decreasing k in leads to:

1- Decreasing structure natural frequency, which could cause an issue if the natural frequency selection is critical in a certain system
2- Less mechanical restoring force, which make the structure more subjectable to stiction forces (see 5.1.2)
3- Lower switching speed

3.3.1.5 Simulation of different cases to reduce actuation voltage for a design example using COMSOL Multiphysics

In this section we present a very simple switch structure (Figure 7), the final switch structure (Figure 8) and present in Table 1 how each change affected displacement actuation voltage. All simulations are done on COMSOL Multiphysics Platform (Check Appendix A)

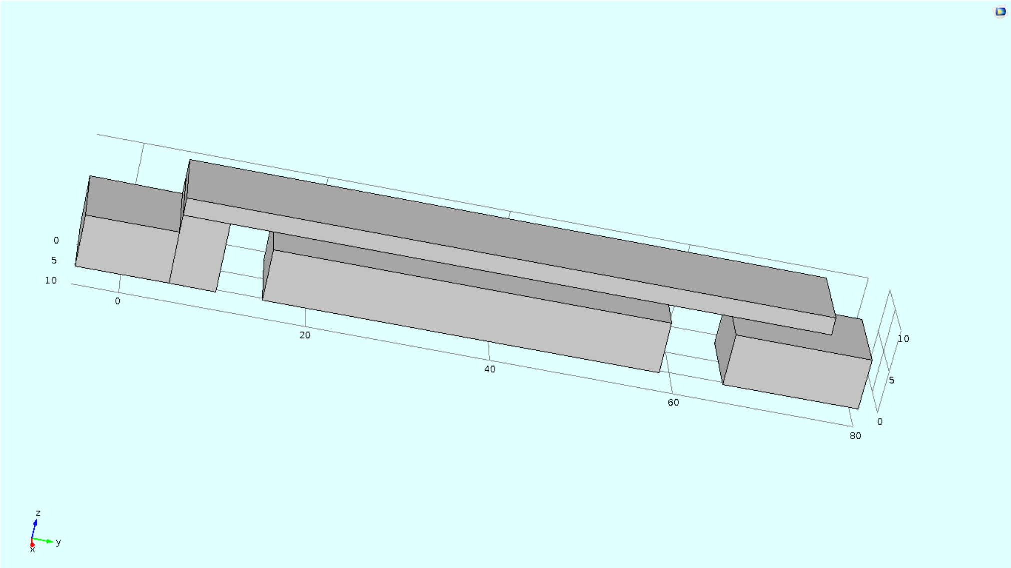

Figure 7: Simple RF MEMS switch

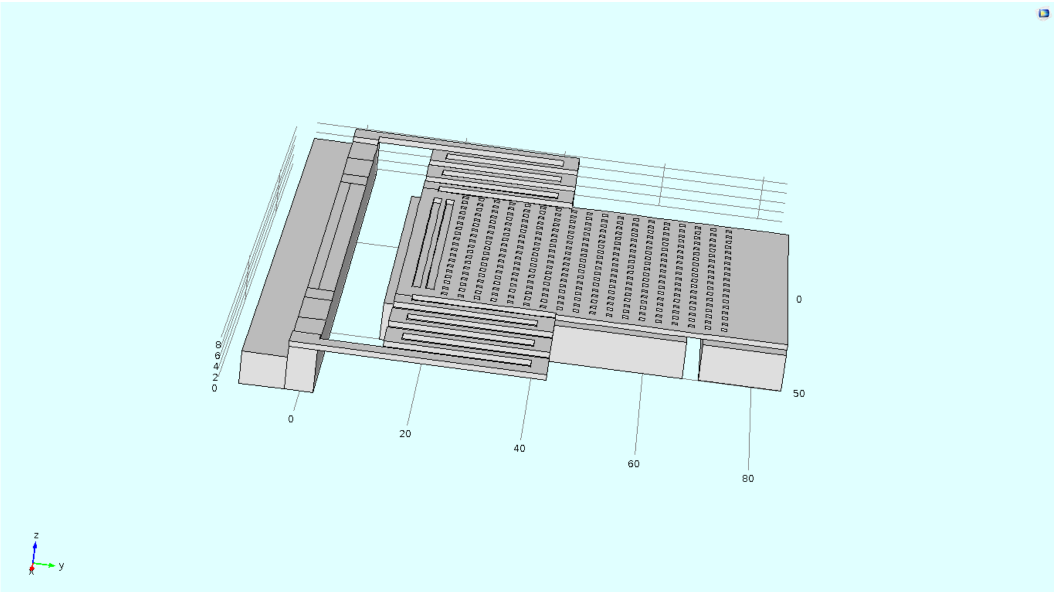

Figure 8: Modified RF MEMS Switch (Low Voltage Actuation)

Table 1: Summary of simulation results after each change in model design parameters

Voltage (V)	**Improvement**	**Displacement (µm)**
10	Simple cantilever	.016
10	Adding 1 Meanders	.09
10	Adding 2 Meanders	.15

10	Meanders + beam thickness reduction from 2 to 1 um	1.52
3.3	Same as above	.13
3.3	Air gap from 2 to 1 um	.62
3.3	3 Meanders	.92
3.3	Longer Meanders	.97
3.3	Longer Cantilever	1.1

Increasing meanders decrease stiffness, decreasing beam thickness also decrease stiffness, decreasing air gap increase electrostatic force, longer meanders or cantilever results in decrease in stiffness. Following the relations described above (before this section) we can find that the modifications and their corresponding displacements (shown in the previous table) correspond to what would be expected.

3.3.2 Stiction Issue

Attractive surface forces play an important role in the behavior of many micromachined structures with contacting surfaces. Capillary, electrostatic forces, and molecular van der Waals can easily interfere with the normal operation of such tiny devices, if surfaces touch each other [5]. These forces have the same order as the actuation forces that can be intentionally generated on a microscale to separate the surfaces. Many micromachines such as switches, depend for their functionality on the contact and separation of surfaces. In many other applications, large surface areas close to each other are common in surface micromachining, and although they are not intended to contact each other, they may come together accidentally.[6]

When the surface forces are too large, the surfaces cannot be separated again, and the micromachined device ceases its intended operation by a failure mode called stiction (Figure 9). Stiction (short for: static friction) is one of the main failure modes in micro electromechanical systems (MEMS), and as such, considerable research has gone into the description of the phenomenon.[6]

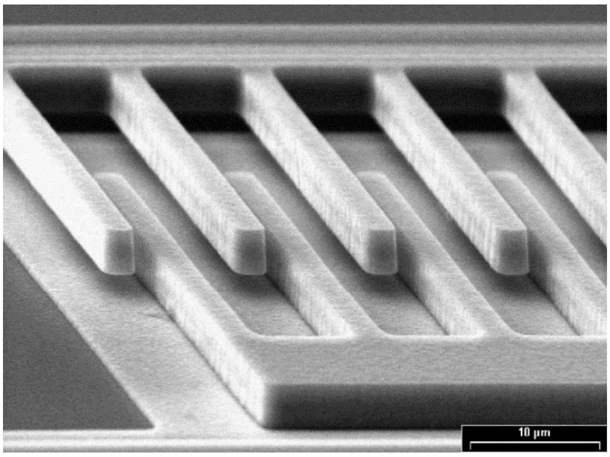

Figure 9: Scanning electron microscope picture of stiction failure in a comb drive.[6]

3.3.2.1 Stiction Forces

3.3.2.1.1 Stiction forces and the properties of contacting surfaces

When the surfaces are very close together, the attractive forces between them will be large, because the surface forces causing stiction depend on the separation distance. It is advantageous to calculate the stiction force effect in terms of *adhesion energy*, the energy required to separate the surfaces once they are in contact [7].

Even the very smooth surfaces of MEMS devices are considered rough on a microscale, and it turns out that this roughness is of the same order as the distance over which many surface forces act. And so, the roughness of the contacting surfaces is an important aspect of the description of stiction.

When two surfaces come together, only the highest parts (asperities) will touch each other (Figure 10). Every single point on the surface at a given distance from the other surface will yield a contribution to the overall adhesion energy. Thus, we have to investigate how much surface area can be found at a certain distance from the other surface to calculate the force when the surfaces adhere. Not only the points in real contact contribute to the adhesion energy, but also parts of the surface that are near the other surface without actually touching it. When all contributions of the different forces are added together, the total adhesion energy is obtained, which is a measure of the energy required to separate the surfaces. We will now investigate the nature of the forces and show the results of the modeling.[6]

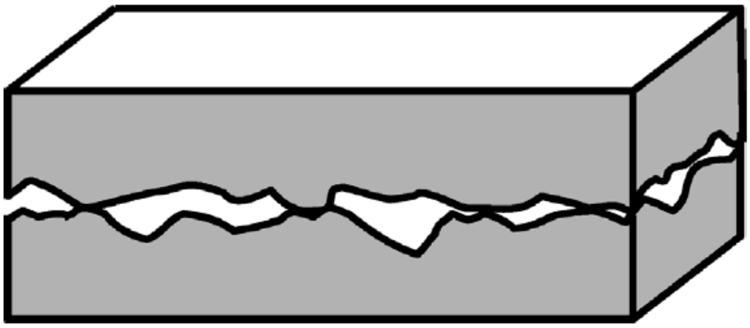

Figure 10: When two rough surfaces stick together, only a small part of the surfaces is really in contact.[6]

3.3.2.1.2 Capillary Condensation

The strongest surface force is caused by water between two surfaces in a humid environment. Water vapor tends to condense in small cracks and pores and forms a thin water film at the contact points of the surfaces by a process called capillary condensation (see Figure 11).

Changes in surface roughness, temperature and the relative humidity affect water surface coverage. Thus changing adhesion energy.[6]

3.3.2.1.3 Van der Waals forces

The molecular van der Waals forces are weaker than capillary forces unless the RH is low (<30% RH) or the surface roughness is very low (<1 nm). Another situation where van der Waals stiction is observed is in MEMS with water-repellent coatings.

Attractive force falls off much faster at distances larger than about 20 nm, which is usually taken as a cut-off distance for the van der Waals forces. Atoms will repel each other when they are so close that their electron-shells are deformed at about .165 nm. There will be no part of the surfaces with a distance between them less than this distance.

When the surface roughness is low, a large part of the surfaces will play a significant role in the stiction behavior, whereas when the surfaces are very rough, only a small part of the surfaces will be involved.[6]

3.3.2.1.4 Electrostatic forces, H-bridging and solid bridging

Electrostatic forces may occur between MEMS surfaces due to differences in contact potential, turbocharging of rubbing surfaces, and ion and/or electron trapping in oxide layers.

When charging of dielectric layers due to charge injection is a problem, the accumulation of carriers can be prevented by lowering the resistivity of the dielectric.

This can, for example, be accomplished by doping the dielectric. For example, the conductivity of Si_xN_y depends on the percentage of Si in this dielectric. Changing the Si content of Si_xN_y was successful in the design of a capacitive RF-MEMS switch [8].

Another stiction issue is present when hydrophilic surfaces are in a completely waterless environment. These surfaces are often covered with OH groups attracting each other because the O-atom has a slight negative charge and the Hatom has a small positive charge due to electronegativity differences between the two elements. With completely flat surfaces, their effect would be considerable, as was calculated by Legtenberg et al. [9]. It would result in 0.1 to 0.3 J /m2 adhesion energy, comparable to the effect of capillary adhesion due to condensed water completely covering the surfaces. However, H-bond forces are very short ranged (the typical length of an OH O bond is 2.7 Å [10]). The actual contact between two surfaces occurs at only a few contact points with a small overall contact area [11], and, therefore, H-bonding is not significant for rough surfaces in contact. Solid bridging can be another reason for stiction. Unfortunately, solid bridging is a term used for two vastly different phenomena. The first phenomenon is the 'cold welding' of metallic surfaces during operation of a MEMS device. In soft metals without chemically different surface layers it occurs spontaneously [12]; while in hard metals, it will appear due to a current flow from one surface to the other. The second phenomenon is related to stiction due to the release process of MEMS devices. When MEMS devices are dried after the release etch by just evaporating the liquid in which they were immersed, surfaces are often pulled into contact due to capillary forces. When the liquid evaporates completely, it can leave a residue of concentrated impurities, which can form a solid bridge from one surface to the other thus gluing them together.

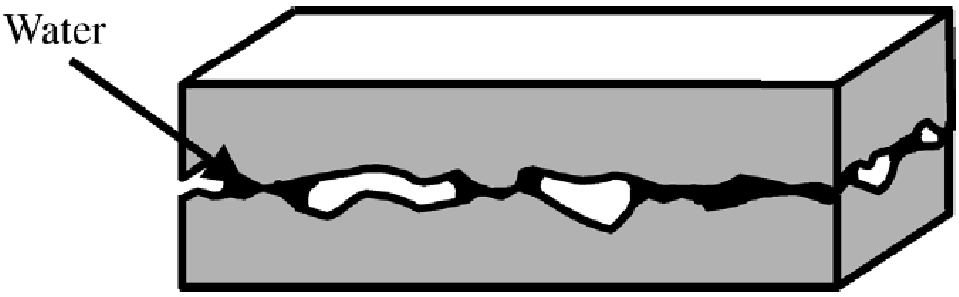

Figure 11: Capillary condensed water

3.3.2.2 Prevention of Stiction Failures

Stiction will only occur when two requirements are fulfilled. The surfaces have to be in contact, at least for a little while, and the adhesion energy of the surfaces has to be larger than other forces acting on the surfaces (i.e. spring force of the device, electrostatic actuation with a counter electrode).

In the previous sections, we have seen that stiction is caused by different forces. As not all forces depend on the same conditions, different solutions are required to eliminate the different adhesion energy components. The most problematic of them by far — from a practical point of view — is the capillary force. Therefore, most activities related to stiction reduction are primarily concerned with the amount of water between the surfaces of a MEMS device.

We have seen that capillary stiction depends on the possibility of water to wet the surfaces and the amount of the rough surfaces nearer to each other than a specific distance which, in turn, depends on the relative humidity and temperature of the surrounding. Thus the main approaches one can take to counteract humidity related forces are:

- The use of rough surfaces (not much surface area in intimate contact),
- The use of hydrophobic surfaces (no capillary condensation),
- Prevent water in the environment.

Electrostatic forces due to dielectric charging can be prevented by increasing the conductivity of the dielectric.

The fourth (and maybe most important) anti-stiction related solution is:

- To have a structure which is as stiff as is possible, so that restoring forces can separate contacting layers. We will now treat these subjects separately.

3.3.2.2.1 Preventing stiction by design

Introducing reliability issues in the earliest stages of the design, or 'design for reliability' is gaining more and more acceptance, as it enables the designers to cope with reliability issues early, thereby reducing the number of prototype cycles.

Since stiction is among the top concerns in MEMS, one should estimate the worst-case adhesion energies to be expected at the beginning of the design. One can perform mechanical simulations — analytical or with finite element modeling

(FEM) — to test the spring and actuation forces in the design. If they are large enough to separate sticking surfaces under all conditions, many problems can be circumvented.

If the modeling shows that the stiction problems cannot be prevented completely by the design of the device, as is often the case with the very large compliances encountered in MEMS, one can resort to one of the approaches below. Most of them have the advantage that they can be used as an add-on, after the fabrication is completed. However, it is good to know whether such process steps are required, before the first prototype is released.

If stiction reducing processes are used, one has to know the effect of the additional process (in terms of reduction of the adhesion energy per unit area) to find whether it is sufficient to effectively eliminate stiction failures.[6]

3.3.2.2.2 Preventing stiction by roughening and skewing the surfaces

The most intuitive solution to decrease stiction problems due to capillary and van Der Waals forces is texturing the surface. The surface forces depend critically on the distance between the surfaces, so it is advantageous when a large part of the surfaces is not in close contact. This surface texturing can be done in different ways.

The use of bumps or 'spacers' on contacting surfaces effectively reduces the area of intimate contact [5][13]. Roughening of the surfaces is another option. The third is to modify the distribution of surface heights from nearly Gaussian to one having a considerable skewness (asymmetry). An extreme form of this skewness is, of course, the previously mentioned method with bumps or spacers. A review of methods to alter the surface topography is given in the papers by Maboudian and Howe [14] and Komvopoulos [15].

For silicon MEMS, to roughen the surfaces after the structures have been released seems to be the most common method in the scientific literature. The main idea is to exaggerate the existing roughness by using a selective etch. This can be done, for example, by using longer HF or (better) BHF (HF with a buffering salt) etch times, resulting in an over-etch of the Si MEMS structure, or by etching in a CCl4 /He/O2 plasma after the release has been completed. The last method etches slowly through the SiO2, and then the etching speed is increased when it reaches the silicon.

Due to non-uniformity of the oxide layer thickness, the silicon is etched earlier at some parts of the surface than on other parts, increasing the surface roughness considerably. NH4F etches silicon preferably along the (100) crystal plane, thus it can be used to create small pyramids on the surface. Another way is to change the deposition conditions of the structural layers in such a way that rougher layers are deposited in the first place [14].

The MEMS surface roughening should not be overdone. Many MEMS devices, such as capacitive switches, rely for their operation on smooth surfaces. Wear in a MEMS device with sliding contacts can be a limiting factor too. And, last but not least, surface micromachined MEMS have thin structural parts that an extensive roughening of the surfaces can change the mechanical behavior of the device. If roughening of the surfaces alone is not enough, or is undesirable, one can use coatings on the surfaces or getters in a hermetic package to reduce stiction.

3.3.2.2.3 Preventing stiction by using anti-stiction coatings

Already in 1950, Bowden and Tabor [12] used a molecular coating to prevent cold welding caused stiction of a smooth indium ball when pressed against a hard substrate. It worked well, but it was noticed only later that such a layer was also good in preventing stiction due to capillary condensation.

In the 90s the use of anti-stiction coatings emerged to alleviate this problem. These coatings cover the surfaces of a MEMS device with molecules having long hydrophobic hydro- or fluorocarbon chains.

3.3.2.2.4 Preventing stiction by using getters

A completely different solution is to remove all water from the package by using vacuum encapsulation or filling the encapsulation with an inert gas. Gas filling is feasible, but trace amounts of water still can play havoc. For a ‘good’ vacuum, the use of molecular getters has been proposed [16], as is common practice in both radio-and CRT- (cathode ray) tubes. Usually, getters are sputtered reactive metals such as Ti, Ba and Mg. By reacting with the water molecules in the package after it has been sealed, a virtually waterless environment is created and maintained. Common getters such as these reactive metals will also react with oxygen and nitrogen, so that only traces of noble gases remain in the package. A commercially available getter for MEMS by Cookson Electronics is currently on the market [16]. It is a selective, water binding layer, which can be placed, for example, on the inside of the cap of the zero level package (a small on-wafer encapsulation within the normal package) of a MEMS device.

3.3.2.2.5 Preventing stiction by using leaky dielectrics

Apart from the interface forces such as capillary and van der Waals, the most important stiction problem in MEMS is caused by dielectric charging. Electrostatic MEMS devices are operated at high voltages, which generate high electric fields. A 20 V applied across a 200 nm thick dielectric film will cause an electric field of 10^8 V/m. Field strengths of this magnitude may give rise to Schottky injection and Poole-Frenkel type conduction mechanisms [17]. The charges injected will cause trouble if their time constant is long compared to the mechanical movements of the MEMS device.

A solution to this is the use of higher conductivity dielectrics, in which the charges will flow away more easily. In RF-MEMS switches, a reduction of the resistivity of the Si_xN_y dielectric from 10^{11} to 10^7 Ω cm by increasing the silicon concentration in the film prevents the stiction failures typical of this kind of devices [8].

3.3.2.3 Stiction and the Reliability of MEMS

When MEMS surfaces touch each other, there are three possibilities: either the structures stick together forever, they separate immediately, or there is a finite chance that they remain stuck, but also a finite chance that they will not remain stuck. These possibilities may change over time due to changes in the environmental conditions or even in the surfaces themselves.[6]

3.3.2.3.1 Hermiticity of packages

Water entering a package can increase the capillary forces and also increase the stiction susceptibility. The previously mentioned getters may alleviate this problem, but the main concern is still the hermiticity of the package. To test the hermeticity of packages, usually standard gross- and fine-leak tests are used, but they can in some cases be insufficiently sensitive to the small cavities in which MEMS devices are packaged.[6]

3.3.2.3.2 Lowering of the restoring force due to creep

Creep is known to cause more severe problems than fatigue [18] by lowering the restoring force available. The lowered restoring force will result in a stiction failure, and the reason for the failure is not always easy to find.

The only publicly available source of information on the degradation of metals due to creep in moving MEMS is the research done by Texas Instruments (TI) on the Digital Micro-mirror Device (DMD). They found that thin film surface micromachined structures made from aluminum (Al) were much less susceptible to metal fatigue than their macroscopic counterparts. However, creep (the slow movement of atoms under mechanical stress) was much more severe in metal microstructures than expected from their macroscopic behavior [18]. It is expected that this kind of creep will ultimately limit the lifetime of all low melting point metals used in MEMS for structural parts under Signiant mechanical stress (a high melting point metal often has a low creep). The creep in Al thin films was so large that TI had to find other materials for the structural beams of their mirrors to obtain a reliable device. To stay compatible with the Al-etch processing which was already in use and well characterized, TI developed Al alloys with much higher melting points. The ones found to be particularly useful were Al_3Ti, AlTi, AlN, and a mixture of AlN and Al_3Ti.[6]

3.3.2.4 Conclusion

The most important techniques to prevent stiction are reviewed from a reliability point of view. There are four ways to decrease stiction problems: (1) use of stiff structures with high restoring forces, (2) use of rough surfaces, (3) use of antistiction coatings, and (4) use of getters in zero- or first-level packages of the MEMS devices.

Probably the best way to analyze in-use stiction failures is to perform practical reliability tests. Some of the forces causing stiction (e.g. capillary) can be aggravated to a certain extent. Van der Waals forces cannot be exaggerated at all, while capillary forces depend on the relative humidity, and slightly on the temperature. Decreasing the temperature and increasing the relative humidity will increase the stiction force. Below 0±C, water between the surfaces may freeze, and may give rise to some very interesting phenomena as well. The hermeticity testing of MEMS packages can be accelerated to monitor water entering the package and changing the MEMS properties. Charging effects of dielectrics that may cause stiction can also be observed, and, in some cases, accelerated. Lowering the resistivity of a dielectric that is prone to charging can diminish stiction due to electrostatic causes. The degradation of restoring forces due to creep takes place faster at high temperatures, so high temperature tests can be interesting for stiction research as well. [6]

3.3.3 RF Performance

The main parameters, we target in RF performance as mentioned in RF Switches Characterization section, are Isolation and Insertion Loss. To decrease (enhance) IL it's needed to match the design with substrate at i.e. 50 ohm. In metal to metal contact switch, in most cases it's needed to increase the contact area of the switch as possible, but this comes with certain tradeoffs:

1- The switch design or actuation force couldn't support a bigger contact area.
2- The isolation of the switch may be reduced when the intersection area is higher.
3- Area Restriction.

To increase (enhance) isolation it's needed (in metal to metal contact switch) to:

1- Decrease the contact intersection area as possible
2- Increase the gap between broken signal lines (Input & Output)
3- Increase the gap between the floating metal contact and the signal lines

But 1 may lead to increase in IL, 2 increases switch area (lead to tradeoff 1 & 2 in IL) and 3 typically leads to higher actuation force.

An optimization must be done to reach the optimum values of IL, Isolation and other required switch specifications. Optimization steps include sweeping various parameters (multiple parametric simulations) to choose the optimum values of switch structure.

3.3.4 Power Consumption

In both piezoelectric and electrostatic actuation, the power consumption is very low in the range of μWs. Higher power is consumed in Thermal and Magnetic actuation techniques as in the latter there is current flowing, but for the piezoelectric and electrostatic actuation, the current only flow in the dynamic behavior (when the switch move from off to on or from on to off, similar to CMOS Technology).

3.3.5 Fabrication

Typically in MEMS, there is a main objective that is to reduce the fabrication complexity. Complexity maybe due to (and not limited to):

1- Increasing used layers
2- Very small dimensions
3- Using uncommon materials
4- The design needs special packaging (i.e. sealed hermetic package to prevent water vapor)
5- The design consists of multiple parts and needs bonding

So the best choice is meet the required Specification with minimum fabrication complexity. (Simplest Design)

3.3.6 Natural Frequency

Definition: is the frequency at which a system tends to oscillate in the absence of any driving or damping force.[19]

Decreasing structure mass and increasing structure stiffness results in high natural frequency.

The importance of structure natural frequencies, is that it’s needed to avoid that the structure oscillates (vibrates) near that frequency, as it would lead to instability and may damage the structure or even break it.

In general we need to design the natural frequency as high as possible from two possible situations values:

1- If the switch is installed in a certain machine that vibrates (i.e. mobile phone vibrates when it rings with a certain frequency, and also vibrates due to human movements; either walking, running…etc.).
2- The frequency of switching the switch.

Chapter 4: MEMS RF Switch Library

Different MEMS RF switches developed between 1994 and 2002 by Industry, University, and Government Laboratories will be presented in this chapter showing their structure and performance.

4.1 THE RAYTHEON CAPACITIVE MEMS SHUNT SWITCH

The Raytheon shunt switch, also known as the Texas Instruments Switch, was developed by Chuck Goldsmith and his co-workers in 1995–2000 [20]. The Raytheon switch is very similar to the standard MEMS capacitive switch shown in Chapter 4, and it has undergone three main iterations to result in an outstanding MEMS capacitive switch (Figure 12). The bridge membrane is composed of 0.5-mm-thick aluminum that is suspended 3–5 μm above the t-line. A tungsten-alloy electrode is used underneath the bridge so as to result in a very smooth dielectric layer (1000 A˚ of nitride) and an excellent capacitance ratio (80–120). The main characteristics of the switch are presented in Table 2. [3]

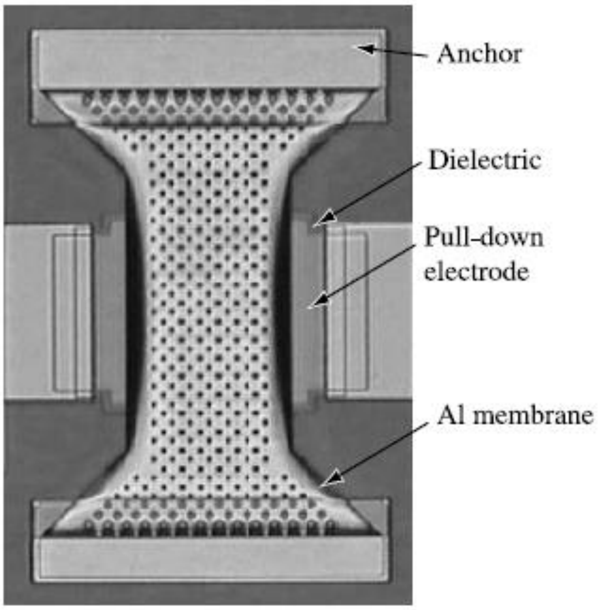

Figure 12. Photomicrograph of Raytheon MEMS capacitive shunt switch (Copyright IEEE)

Table 2. Parameters for the Raytheon Capacitive MEMS Shunt Switch

Parameter	Value
Switching Time (μs)	3/5
Operating Voltage (V)	30–50
Insertion Loss (dB)	-0.07 (10–40 GHz)
Isolation (dB)	-20 (10 GHz)

4.2 THE UNIVERSITY OF MICHIGAN CAPACITIVE MEMS SHUNT SWITCHES Low-Voltage (Low-Spring-Constant) Switch

The University of Michigan has developed a novel low-voltage MEMS capacitive shunt switch [21] (Figure 13). The idea is to suspend the membrane using meander support structures, which results in a low-spring-constant design. The pull-down voltage depends on the number of meander bends used and the thickness of the membrane. A pulldown voltage of 6–12 V can be achieved with this design for a gap height of 4– 5 μm. Also, notice that the capacitive portion at the center of the switch is not used to pull down the switch. Rather, two large pads on both sides of the switch are used as the actuation electrodes. This allows the designer to have an independent control on the pull-down voltage by choosing the size and spring constant of the actuation electrodes.

One of the problems with low-spring-constant designs is their sensitivity to mechanical forces such as acceleration, vibration, and Brownian noise. One way to solve this problem is to fabricate a pull-up electrode above the switch. In this case, the membrane is fixed in the up-state position when the switch is not activated, and therefore the switch is not sensitive to any mechanical forces. Another problem with low-spring-constant designs is their associated slow response times. The top electrode can also be used to reduce the pull-up time response.

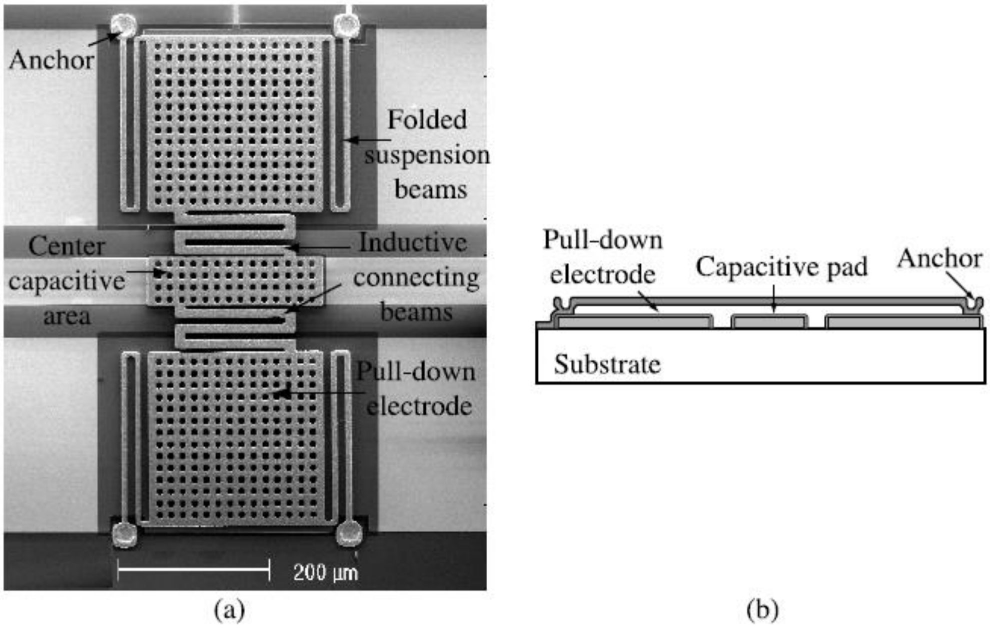

Figure 13. Photomicrograph of the university of Michigan low-voltage MEMS shunt switch

Table 3. Parameters for the University of Michigan Low-Voltage MEMS [3]

Parameter	**Value**
Switching Time (µs)	20–40
Operating Voltage (V)	6–20
Insertion Loss (dB)	-0.1 (1–40 GHz)
Isolation (dB)	-25 (30 GHz)

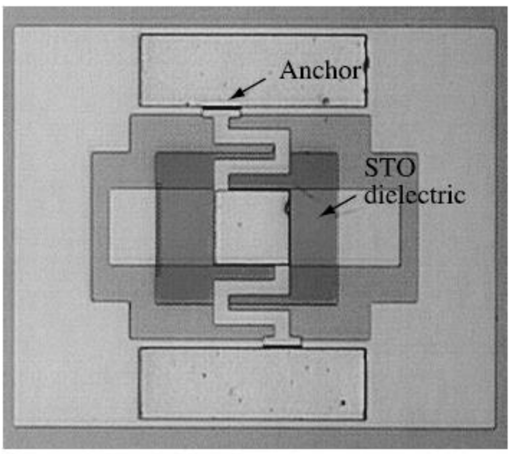

Figure 14. Photomicrograph of the LG-Korea high-capacitive-ratio MEMS shunt

4.3 THE LG-KOREA HIGH-CAPACITANCE-RATIO MEMS SHUNT SWITCH

Park et al. presented a very-high-capacitance-ratio MEMS shunt switch [22].The design is based on the standard fixed–fixed beam capacitive shunt switch, but uses strontium-titanate-oxide (SrTiO3) as the dielectric layer in the switch (Figure 14). STO results in a relative dielectric constant of 30–120, depending on the deposition temperature (30 at 200 degrees and 120 at 300 degrees). The fabricated switches achieved a capacitance ratio of 600 and a down-state capacitance of 50 pF (up-state capacitance of 70–80 fF). Its main characteristics are summarized in Table 4. [3]

Table 4. Parameters for the LG-Korea High-Capacitance-Ratio MEMS Shunt Switch

Parameter	Value
Switching Time (µs)	---
Operating Voltage (V)	8-15
Insertion Loss (dB)	-0.1 (1–10 GHz)
Isolation (dB)	-40 (3–5 GHz)

4.4 THE UNIVERSITY OF ILLINOIS DC-CONTACT MEMS SHUNT SWITCH

The University of Illinois developed a low-voltage DC-contact shunt switch[23], [24]. The low-voltage design is achieved using narrow low-spring constant support beams near the membrane anchor. The switch consists of two pull-down electrodes on both sides of the center portion of the switch (Figure 3Figure 15). It also employs pull-up electrodes to fix the membrane in the up-state position when the switch is not actuated. The switch is fabricated using polyimide as sacrificial layers, and it is released using dry-etch techniques and using 8-µm-diameter holes in the top electrode and the membrane layer. Silicon nitride is used as the insulating dielectric between the membrane and the top and bottom electrodes. The actuation electrode area is $(2) * 800 * 100\ \mu m^2$ with a height of 4 µm, and the resulting pull down-voltage is 9–16 V (Table 5).

One of the advantages of having separate pull-down electrodes is that one can achieve a metal-to-metal contact and a high isolation from DC to mm wave frequencies. The University of Illinois switch was fabricated on a GaAs substrate and results in an up-state capacitance of 40 fF and a down-state contact resistance of 1.2 Ω.

Table 5. Parameters for the University of Illinois DC-Contact MEMS Shunt Switch

Parameter	Value
Switching Time (μs)	---
Operating Voltage (V)	9-16
Insertion Loss (dB)	-0.1 (0.1–40 GHz)
Isolation (dB)	-25 (0.1–40 GHz)

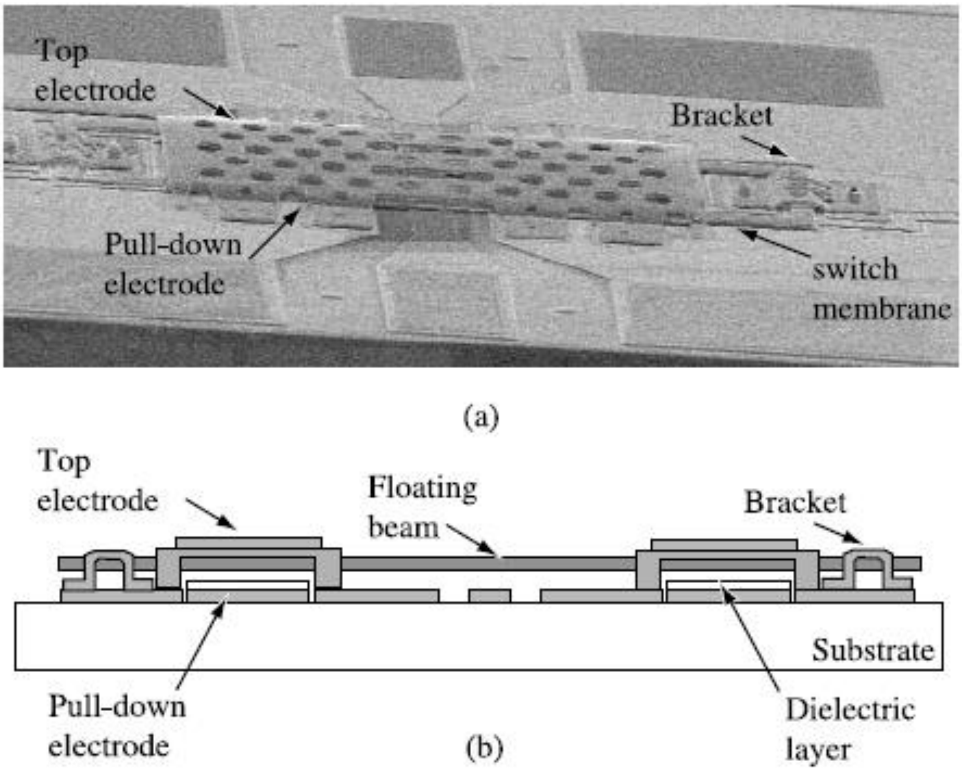

Figure 15. SEM (a) and cross section (b) of the University of Illinois DC-contact MEMS shunt switch [23], [24] (Copyright IEEE).

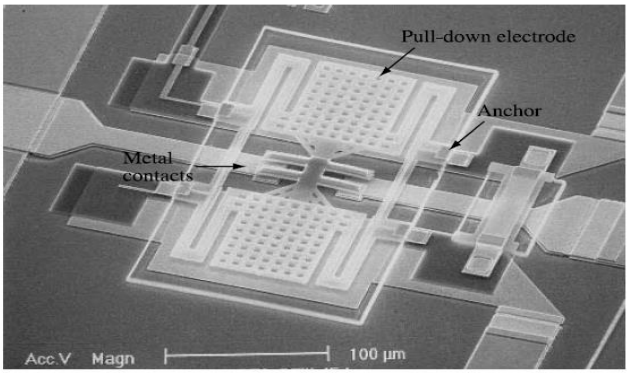

Figure 16. SEM of the Rockwell Scientific MEMS series switch

4.5 THE ROCKWELL SCIENTIFIC DC-CONTACT MEMS SERIES SWITCH

The switch is fabricated using a 2-µm layer of silicon dioxide deposited using a low-temperature PECVD process on a GaAs substrate. The membrane layer is connected to the substrate on four anchor points using a folded spring structure, forming the clam-shell design of Figure 16. The top electrodes have dimensions of 75 x 75 µm2, and they are fabricated using a thin layer of gold (2500 A˚) over a 1-2-µm-thick PECVD silicon dioxide membrane. An array of micron-sized holes is defined in the silicon oxide membrane to reduce the squeeze film damping. The pull-down electrodes are placed 20–40 µm from the microwave t-line. The switch is suspended 2–2.5 µm above the substrate and the pull-down voltage is 60 V. The contact areas are actually made of two pairs of contact ‘‘points,’’ each a few square microns in area, and the contact metal is a 0.5- to 1-µm-thick gold alloy. A dimple process is created in the polyimide sacrificial layer to create the contact points. The switch is released using plasma etching; therefore, no critical point drying is used. The entire switch is around 150 x 250 µm and details of the fabrication process are presented in [25].

Rockwell Scientific MEMS has improved the mechanical aspect of the series MEMS switch by including dielectric dimples in the silicon oxide membrane. These dimples act as a ‘‘stopping’’ mechanism and prevent the membrane layer from making a physical contact with the bottom metal electrode. This design eliminates the stiction problem between the bottom metal and the dielectric membrane, and greatly improves the reliability of the switch. The gap height in the down-state position is 0.5–1 mm. Its main characteristics are summarized in Table 6. [3]

Table 6. Parameters for the Rockwell Scientific DC-Contact MEMS Series Switch

Parameter	Value
Switching Time (µs)	8-10
Operating Voltage (V)	50-60
Insertion Loss (dB)	-0.1 (0.1–50 GHz)
Isolation (dB)	-30 (40 GHz)

4.6 THE MOTOROLA DC-CONTACT MEMS SERIES SWITCH

Motorola developed a compact DC-contact MEMS series switch on silicon substrates (Figure 17). The switch is based on a 1.0- to 1.5-µm-thick PECVD SiO2 cantilever with dimensions of 140 x 100 μm^2, including the hinge and anchor. The top metal is a gold alloy and is 2000–4000 A° thick. The cantilever is suspended 2–3 mm from the substrate and the pull-down is 50–60 V. An array of 8 x 8-µm2 holes is defined in the silicon oxide membrane to reduce the squeeze film damping. Two contact points, each 1 x 5 µm2, are defined on the tip of the cantilever and are fabricated using a proprietary gold alloy process. The switch resistance is 1–2 Ω. The short length of the cantilever and its 100-µm width result in a stiff mechanical structure with a switching time of 2–4 µs. Also, the cantilever does not contact the bottom electrode when activated. This design eliminates the stiction problem between the bottom metal and the dielectric membrane, and greatly improves the reliability of the switch.

The sacrificial layer is spin-on-glass and the cantilever is released using dry etching techniques. The t-line is 30 mm wide around the switch, and the t-line gap is 30–40 µm. This, together with the small contact areas and the 2- to 3-µm height of the switch, results in an effective up-state capacitance of 2–2.5 fF when the switch is built on silicon substrates. The measured isolation is better than -44 dB at 2.4 GHz. The switch characteristics are summarized in Table 7. [3]

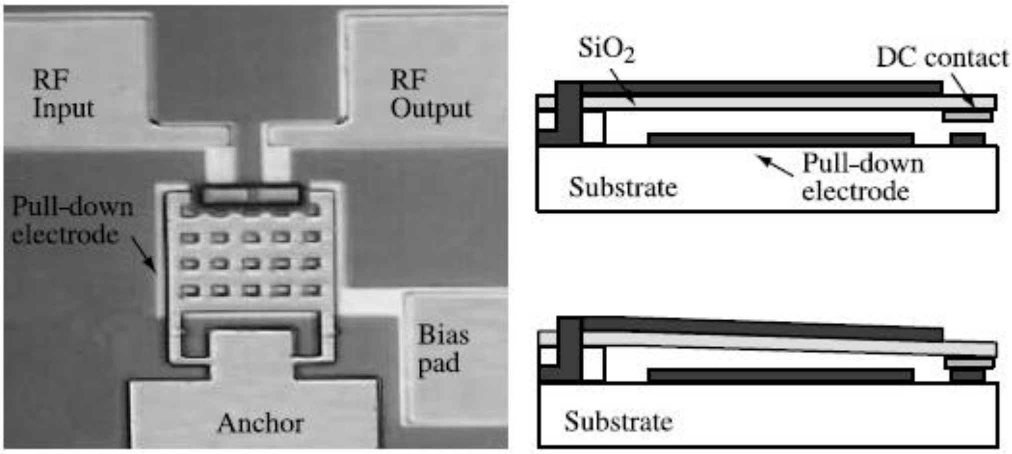

Figure 17. Photomicrograph of the Motorola DC-contact MEMS series switch and cross sections in the up- and down-state positions

4.7 THE HRL DC-CONTACT MEMS SERIES SWITCH

The HRL (formerly Hughes Research Laboratories) series MEMS switch was developed by Hyman et al. in 1998–2000 on GaAs substrates. It consists of a 2-µm-thick PECVD silicon nitride cantilever with a 2.2- to 2.5-µm plated gold layer, along with a 1-µm dimple for the gold-alloy contacts (Figure 18). The entire cantilever is capped with 0.5–1 µm of silicon nitride for stress compensation and protection from the elements. The pull-down electrode is 100 µm2 and is placed 30–40 µm from the microwave t-line. The switch is suspended 1.5–2.0 µm above the t-line, where the height is defined from the bottom of the dimple metal to the t-line. The switch cantilever is flexible and makes intimate contact with the bottom pull-down electrode when the contact area is around 20 x 20 µm2 on each side of the switch, and the gap in the t-line is 60 µm. The switch is fabricated on GaAs wafers, and the input and output lines are 60 µm wide (nominal 50 Ω on a 100-µm-thick wafer). The switch characteristics are summarized in Table 8. [3]

Table 7. Parameters for the Motorola DC-Contact MEMS Series Switch

Parameter	Value
Switching Time (µs)	2-4
Operating Voltage (V)	40-60
Insertion Loss (dB)	-0.15 (0.1–6 GHz)
Isolation (dB)	-44 (2-4 GHz)

Table 8. Parameters for the HRL MEMS Series Switch

Parameter	Value
Switching Time (μs)	2-4
Operating Voltage (V)	40-60
Insertion Loss (dB)	-0.15 (0.1–6 GHz)
Isolation (dB)	-44 (2-4 GHz)

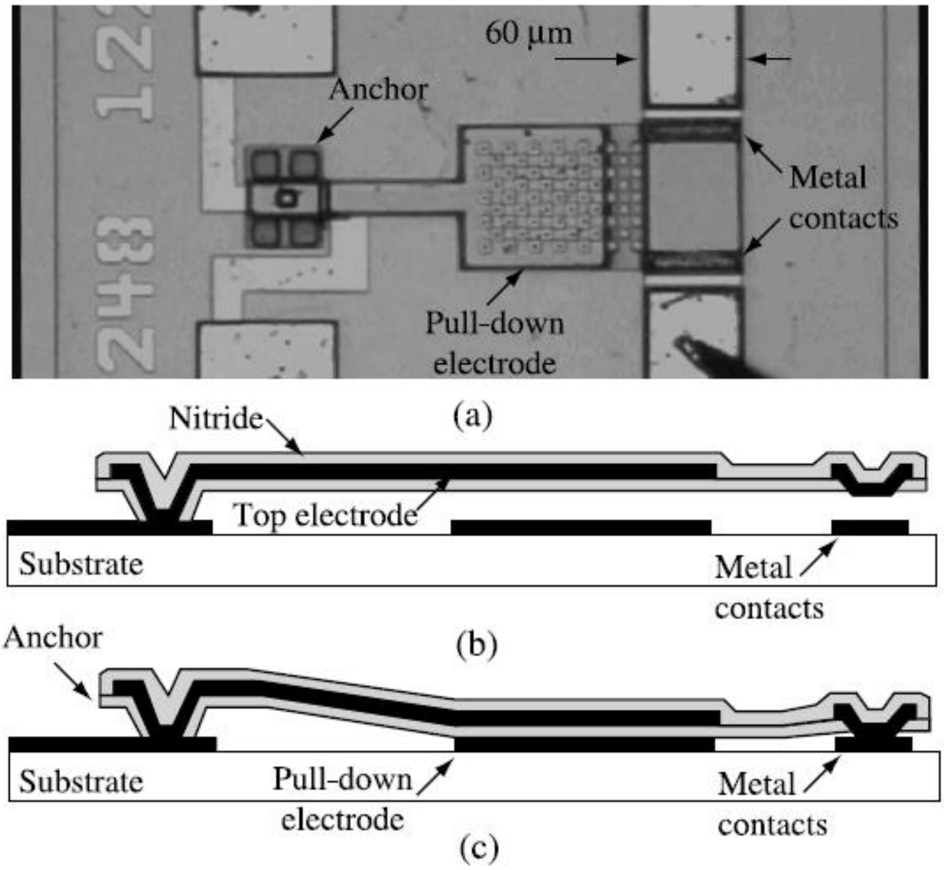

Figure 18. (a) Photomicrograph and (b),(c) cross section of the HRL MEMS series switch

Chapter 5: Required Switch Specifications

Attached in Table 9, the required RF switch specifications. These specifications are needed to be integrated with a research project on a microstrip reconfigureable antenna that Dr. Adham Naji at Britich University in Egypt is currently working on.

Table 9: Required RF Switch Specifications

Specifications	**Value**
Dimensions	Max 1*1 mm^2
Rated Operating Voltage	Low (best 3.3v)
Power Consumption	Low (in µW)
Durability	High as possible
Insertion Loss	<0.1 dB Through Frequency Range
Isolation	>30 dB Through Frequency Range
Switching Speed	Low
Frequency Range	.8-6 GHz
Power Handling	Max 1000mW

Chapter 6: First Proposed Design

This design had been submitted as a paper and accepted at IEEE SOCC 2016 (Currently in Press), as:

Elmassry, M., M. Medhat, and H. Mostafa, "Novel Ultra Low Voltage Mobile Compatible RF MEMS Switch for Reconfigurable Microstrip Antenna", *IEEE International System on Chip Conference (SOCC'2016)*, Seattle, WA, USA, IEEE, In Press.

6.1 Structure and principle of operation

6.1.1 Structure

The proposed switch consists of two almost symmetric parts, each consists of a perforated cantilever, up electrode, down electrode and RF port as shown in Figure 19

6.1.2 Cantilever

A gold cantilever of length 220 µm and width 100 µm fixed from one end with holes to reduce air damping [3] of diameter d=1 µm with separation (S) of 3 µm between adjacent holes and the air gap between cantilever and electrode (g_0) equals to 0.5 µm. The effect of the holes on the up-state capacitance is negligible if the diameter of the holes is less than 3–4g_0 [3]. The entire cantilever is capped with 0.4 µm of Silicon nitride for stress compensation, protection from the elements [3], to prevent short circuit between cantilever and electrode and also to isolate the floating contact metal from the grounded gold layer used for the electrostatic actuation. The air gap between the two cantilevers is 1 µm.

6.1.3 Electrodes

The switch uses dual supply lines, using 4 electrodes, each two electrodes are controlled together (connected to the same supply line), one to pull down the left cantilever and the other to pull up the right cantilever and the two other electrodes, one to pull up the left cantilever and the other to pull down the right cantilever as shown in Figure 20. Both up electrodes are relatively thick and properly anchored to be considered fixed thus the cantilevers are the only moving parts of the structure.

6.1.4 Anchors

Five anchors are used for fixing, right and left cantilevers, up electrodes and RF output port.

6.2 Principle of Operation

The cantilever is always connected to ground and the electrodes are the controlled elements (by applying a voltage waveform). The switch operation is based on two states: the off state in which the left cantilever is pulled up and the right one is pulled down resulting in high isolation in this case.
The other state is the on state in which the left cantilever is pulled down to touch the RF input port and the right is pulled up to touch the RF output port and the two cantilevers contact each other causing metal to metal contact between the two RF ports.

This switching technique makes the structure less subjectable to vibrations, for a low gap height the isolation is still high (as the up state double the normal gap height and also the up-state capacitance is modeled in the Electromagnetic Modeling Section (5.4) as 3 in series capacitors which results in lower equivalent total capacitance), though structure stiffness is low thus the restoring forces are weak.

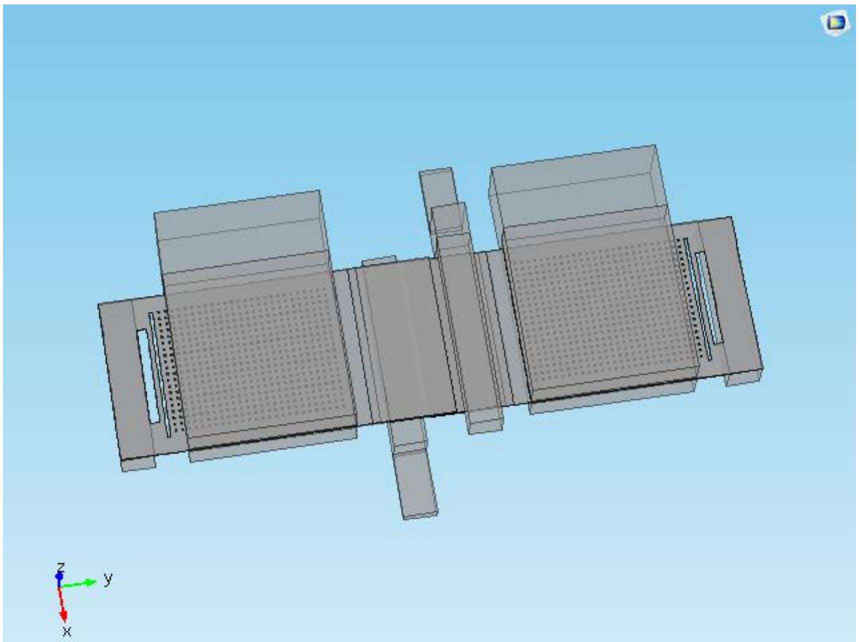

Figure 19: Tilted semi-transparent view of the switch structure (substrate not shown)

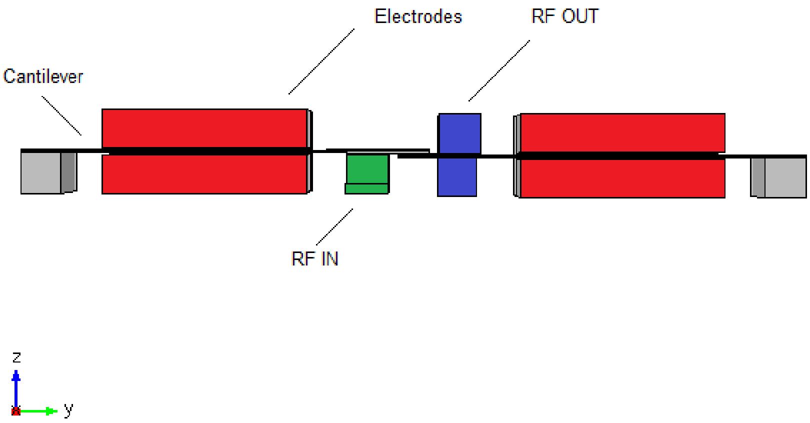

Figure 20: Side view of the switch

The structure can return from either ON or OFF states and a faster switching speed as: each cantilever travels only half the distance and the cantilevers have a potential energy in their OFF or ON positions (mechanical restoring forces).

One of the other challenges in the operation of the switch is the failure of the contact due to the impact that occurs each time the switch is turned on, the contacts hit each other, one way to reduce this effect is to carefully choose the material of the contact. And that would be discussed in the Selection of Materials Section (5.3). Another way to reduce the impact energy is to tailor the actuation voltage wave form as shown in Figure 21. [3]

Another reason that leads to switch failure is the dielectric charging but this is eliminated in this design as the cantilever does not touch the actuation electrodes (the displacement of the cantilever is less than the gap between the electrode and the cantilever) and also a mechanical stoppers maybe added to further prevent the cantilever from reaching the electrodes.

6.3 Selection of Materials

The main reason of switches failure is the contact [3], so the good selection of its material is very important, typically gold is the most suitable material for the contacts, as it has good conductivity, high chemical resistance to corrosion and contamination. Despite its advantages, the gold is a soft metal, so it usually fails due to contact wear or to contact stiction.

In this paper [29] an experimental study shows that stacking thin layers of platinum between gold layers increases gold hardness. Accordingly the contact of the proposed switch is made of gold-platinum-gold layers. (This advantage of course results in a more complex fabrication process)

Note that the switch has 4 contact spots, all to be built as mentioned above; the two cantilevers and the two RF ports contact areas.

Attached in Table 10 switch main components materials and dimensions

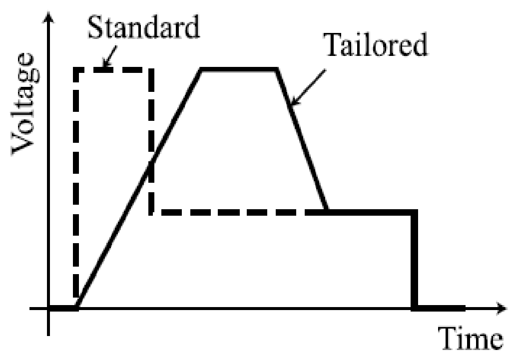

Figure 21: Actuation voltage waveform to reduce the impact energy

Table 10: Main switch structure components specifications

Description	**Specifications (in µm)**			
	Material	***Thickness***	***Length***	***Width***
Cantilever	Si_3Ni_4-Au- Si_3Ni_4	.4-.4-.4	220	100
Electrodes (up & down)	SiO_2-Au	7-.5	120	100
Contacts	Au-Pt-Au	.3-.003-.2	40	100
RF IN Port	Au-Pt-Au	7.3,.003,.2	40	100
RF Out Port (Cantilever)	Au-Pt-Au	6.8,.003,.2	20	100

6.4 Electromagnetic modeling

It is a series metal to metal contact switch working on two states: the ON state and the OFF state. The structure proposed exhibits a very good performance in terms of insertion loss in the ON state and isolation in the OFF state.

6.4.1 Insertion loss

In the ON state, a metal to metal contact occurs between the two signal lines which leads to a low insertion loss compared to capacitive switching technique.

6.4.2 Isolation

In the OFF state, the up state capacitance is approximated as a three in series capacitors between the two signal lines:

1. Capacitance between first signal line (RF IN port) and cantilever contact.
2. Capacitance between the two cantilevers contacts.
3. Capacitance between second signal line (RF Out port) and cantilever contact.

This leads to a low up state capacitance. Leading to high isolation.

6.5 Results

6.5.1 Mechanical

In order for proper switch contact, each cantilever contact must achieve .5 µm displacement to just touch the RF ports and touch each other as well. In real life certain restrictions and mismatches appear as: a low drop in battery voltage (i.e. from 3.3 to 3.2 v), effective contact area is not as the physical contact area due to surface roughness and small mismatches in the fabrication of the switch. That's why the cantilever contact must achieve more than .5 µm to withstand voltage and fabrication variations and increase contact force to increase effective contact area.

The structure is simulated using COMSOL Multiphysics platform.

Several reductions in the model are performed to reduce the computation time and reduce hardware requirements. The structure is modelled as one cantilever, the pull down electrode and a symmetry boundary condition is made to reduce the model to half its original.

6.5.1.1 Displacement

In the shown Figure 22, the displacement of cantilever is plotted against its length, note that the contact length is 40 μm (from 160 to 200 in the figure). The results achieve the targeted displacement (.5 μm) starting from .515 to .65 μm at the tip of the cantilever.

6.5.1.2 Stress

In Figure 23 a maximum stress level is observed to be 38.8 MN/m^2 which is still in the safe range and that value would considerably be dropped if a rounded fillet is used to distribute the stress around the corners.

6.5.2 RF Performance

The RF performance calculations is done using HFSS, the structure is simulated in two positions, ON state (when the contacts be in touched), Off state (when the contacts are separated).

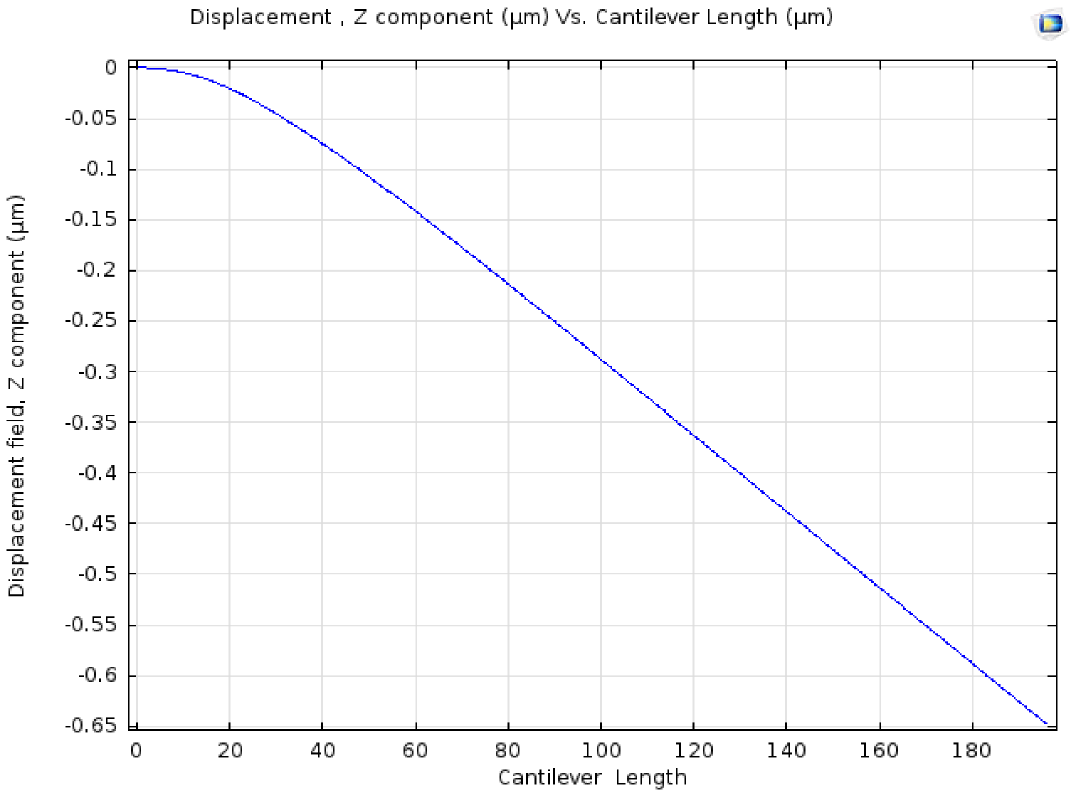

Figure 22: Cantilever Displacement (Z-Component) Vs. Cantilever length in μm on COMSOL Multiphysics Platform

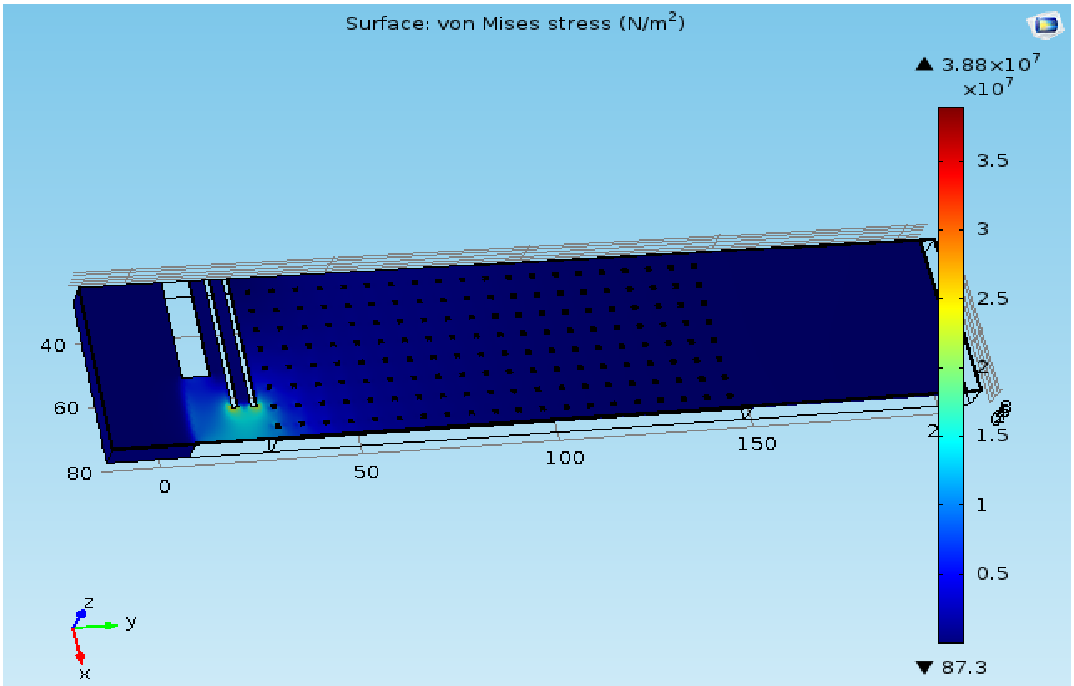

Figure 23: Stress distribution on the switch structure, half model only without the up electrode and RF port on COMSOL Multiphysics Platform

The structure modeled in the HFSS is reduced to two RF ports with 2 hanging metal (Au) plates as shown in Figure 24.

The substrate used to simulate the RF performance is Rogers RO4350 with thickness .168 mm and dielectric constant of 3.48.

Note that in the real life operation the effective contact area is less than the physical contact area and is affected by the contact force and surface roughness. The results shown below are based on ideal contact, that is, when effective contact area=physical contact area. So the RF performance would be degraded in real life tests.

In Figure 25 and Figure 26, it's shown that the switch exhibit excellent RF performance.

Note that these simulations are considered a pilot study to give an indication of the switch RF performance, before fabrication of the switch an accurate study must be done, which includes: exact substrate that the switch would be manufactured on (i.e. Alumina), exact substrate of the reconfigurable microstrip antenna (where the switch would be integrated), full model of the switch included in HFSS (including contact pads and packaging) and taking in consideration the effective contact area.

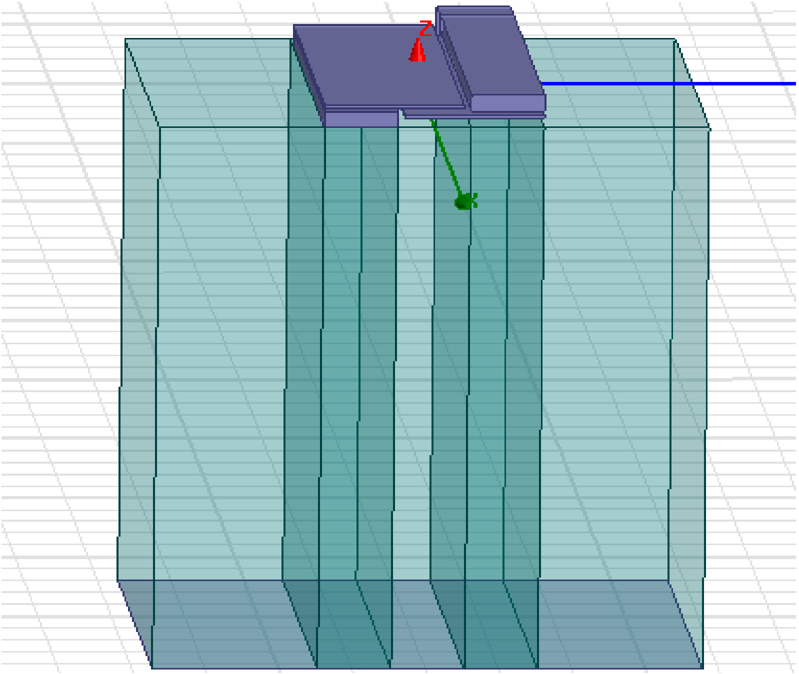

Figure 24: Simplified Structure on HFSS

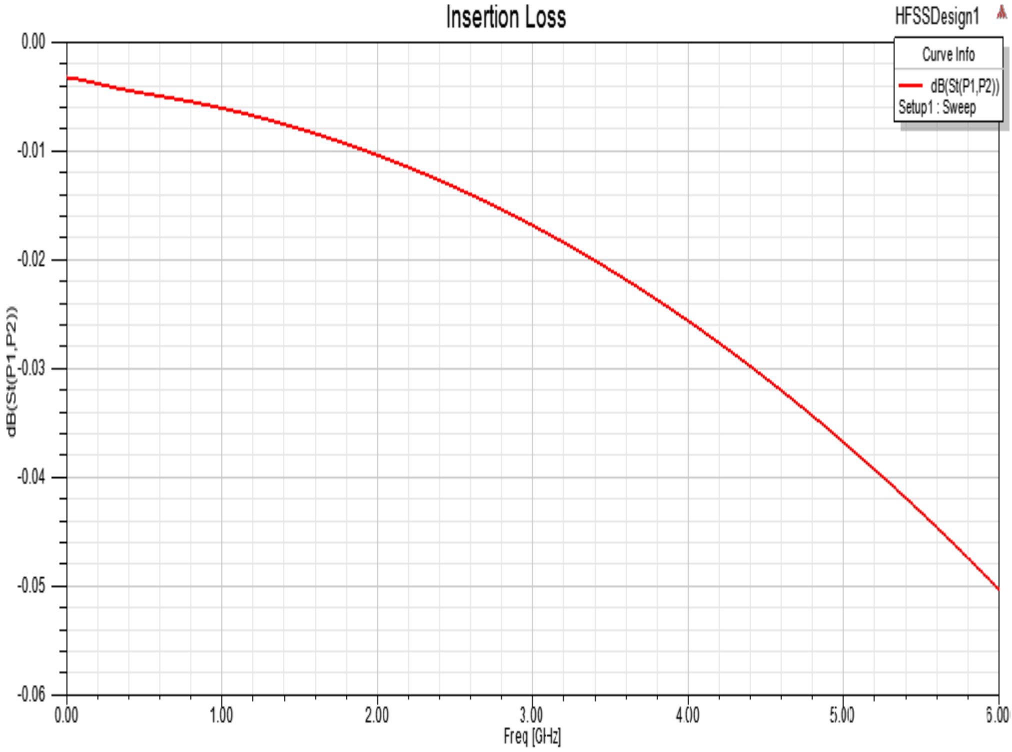

Figure 25: Insertion Loss from DC to 6 GHz on HFSS

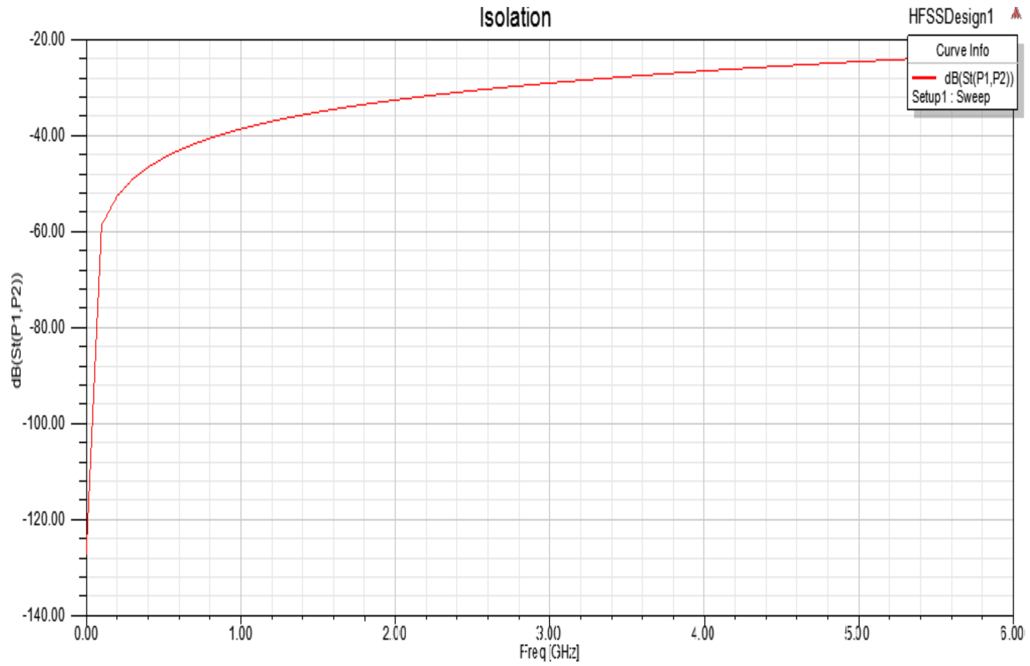

Figure 26: Isolation from DC to 6 GHz on HFSS

6.6 Summary & Conclusion

The proposed design presents a novel RF MEMS switch which is voltage compatible with mobile batteries (3.3 v) operating in the range of DC-6Ghz to be integrated with a reconfigurable microstrip antenna, the switch resulted in excellent performance in terms of insertion loss (.05 dB at 6 Ghz), isolation (21 dB at 6 Ghz), low actuation voltage (3.3 v), low level of stress (< 40 MN/m^2) and is expected to achieve very good life cycles due to its contact material composition and used control voltage waveform. Of course considering latter advantages, a penalty which is the complexity of the fabrication process is paid. Future work may include optimizing this design with current fabrication processes and do real life tests to get exact and acceptable switch characteristics after fabrication.

Due to the fabrication complexity of the proposed switch and it's incompatibility with the current standard fabrications processes. This led us to design another switch that is compatible with fabrication (compatible with UW-MEMS fabrication process), as proposed in the next chapter.

Chapter 7: Second Proposed Design

It is an electrostatically metal to metal contact series switch actuated by 3.3 V to be compatible with mobile's battery.

This structure is built on UW MEMS fabrication process and designed to work at operating voltage compatible with mobile battery (3.3 V).

The process starts with a 0.025" thick Alumina substrate polished on both sides with a relative permittivity of 9.9 and loss tangent of 0.0001 at 1 MHz as shown in Figure 27 .

7.1 Structure

7.1.1 Anchors

The part of the structure that is fixed to the alumina substrate and let the beam hangs freely.

7.1.2 Meanders

Fixed to the anchor and is used to maintain a low stiff beam in order to get a low operating voltage as shown in Figure 30 , however, it may increases sensitivity to mechanical vibrations and this problem could be solved by the double side actuation technique as will be clarified later.

7.1.3 Beam

The beam is carried by the meanders and hangs freely to be actuated by one of the two electrodes on both sides.

The beam consists of two symmetrical parts each has a separate electrode beneath it in order to pull the beam causing either rotating (tilting) clockwise or anticlockwise as shown in Figure 28.

These two states define the on and off either by rotating clockwise causing metal contact between the two lines (ports) or anticlockwise lifting up the beam away from the line resulting in a good RF performance in terms of isolation.

7.1.4 Double Side Electrodes

Two electrodes are placed, each operates separately as shown in Figure 29 .

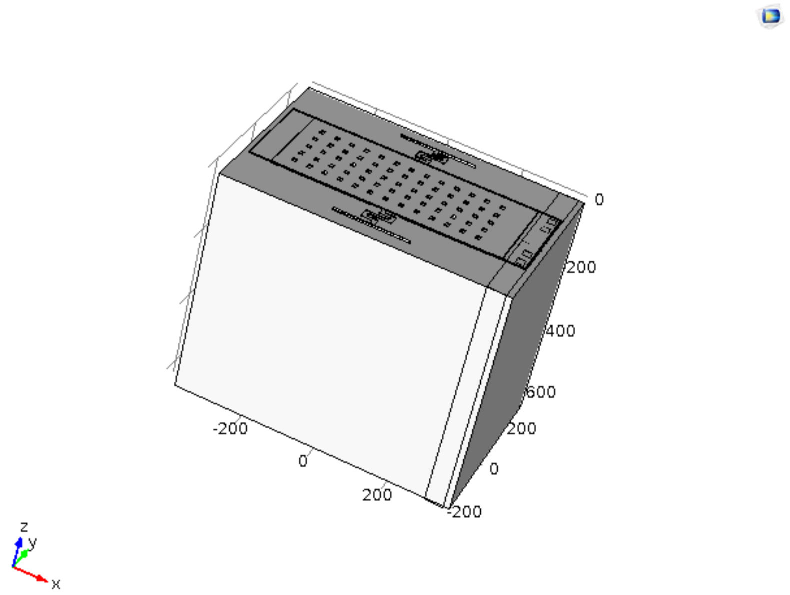

Figure 27. The switch geometry built on alumina substrate

When a voltage difference exists between cantilever and the right electrode, the beam bends (rotates) clockwise touching the two lines resulting in an RF path from input to output.

The same when voltage difference exists between cantilever and the left electrode, the beam bends (rotates) anticlockwise moving away from the two lines leaving them isolated and blocking the RF path from input to output.

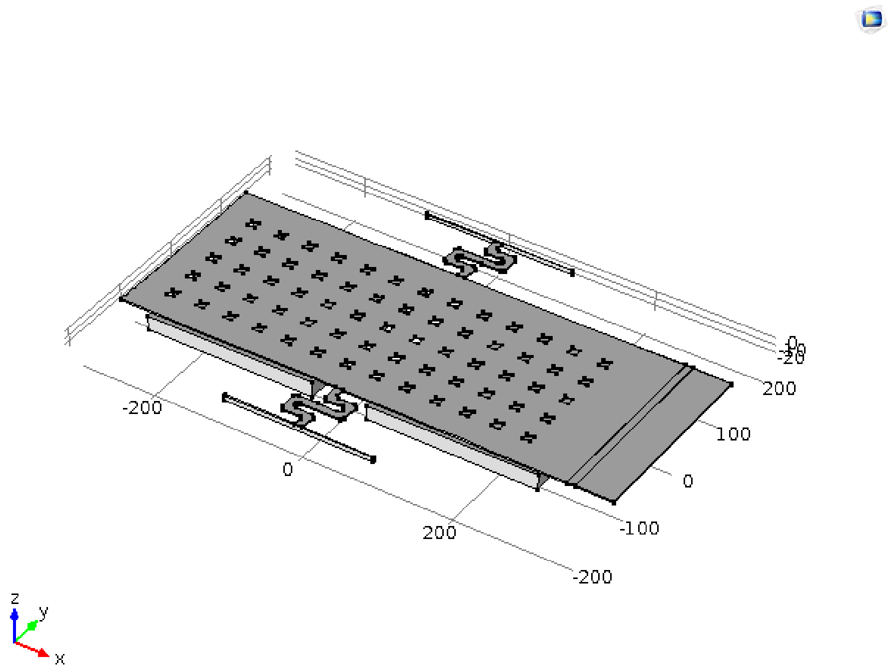

Figure 28. Isometric of the switch structure without the substrate

7.2 Structure's Advantages

The proposed design exhibits good RF performance: low insertion loss due to the metal to metal contact and high isolation as the floating beam moves away from the increasing the distance between beam and the lines resulting in very low up state capacitance.

It is a low stiff structure due to the presence of meanders resulting in 3.3 V which is very low compared to different MEMS RF switches.

To overcome high mechanical sensitivity, two actuation electrodes to have a defined state switch at any time either off or on having the beam in one of two states up or down and that prevents responding to random vibrations or acceleration

Holes are made in the main beam in order to reduce air damping which has an effect of reducing or even preventing the beam to bend.

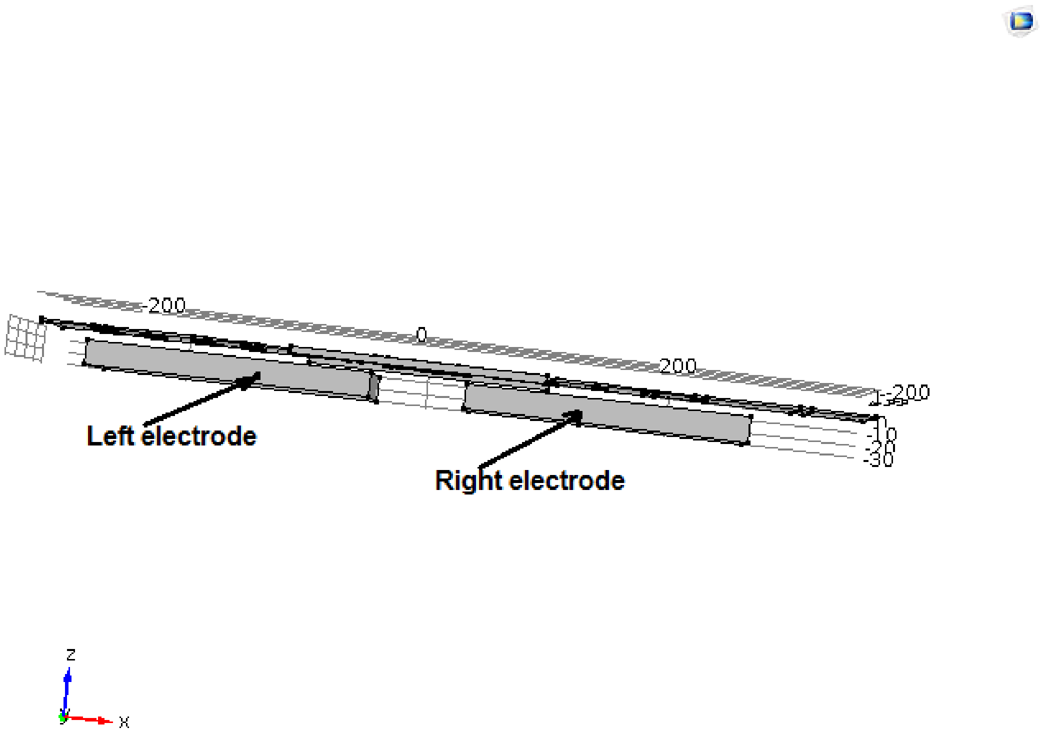

Figure 29. A view of the switch showing the double side actuation electrodes

7.3 Design

Set of parameters are made to reach the required specifications.

7.3.1 Parameters

The parameters mentioned are set for these values in order to achieve certain results that will be shown in the results section.

Choosing the values was based on the typical value of each parameter then tuning to reach the targeted specification.

- **Beam's Dimensions in µm**

  As shown in Figure 31

  - Beam Length=500
  - Beam Width=250
  - Beam Thickness=2

    (Beam thickness is a process dependent parameter and is not tunable)

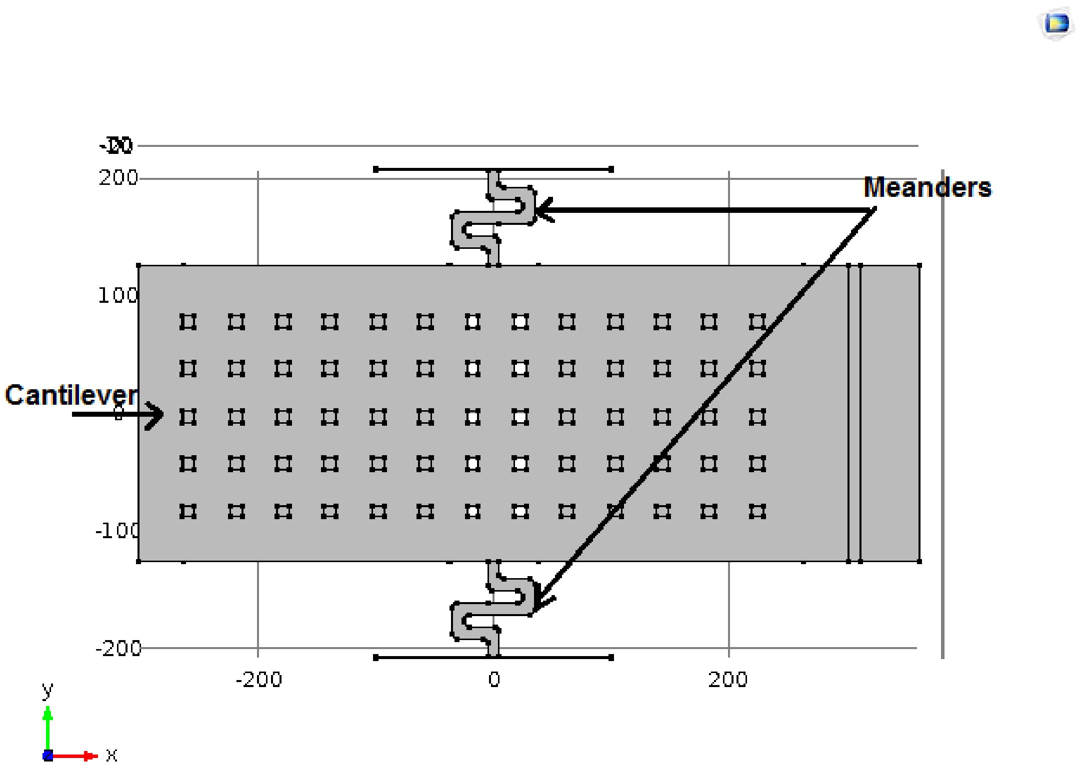

Figure 30. Top view of the switch showing different parts

- **Meanders' Dimensions in µm**

  As shown in Figure 32

  - X Length=50
  - Y Length=80
  - Meander's Width=10
  - Meander's Thickness=2

    (Meander's thickness is a process dependent parameter and is not tunable)

- **Holes Dimensions**
  - Holes' Diameter =10 µm (which is a process dependent and is not tunable)

- **Electrode Area**
  - 187.5*250 μm^2

- **Contact Area**
  - The contact area is the area of the dimples which is equal to $4 * 15 * 15 = 900\ \mu m^2$

    This is ideal area but in the real case the dimple is not flat and the area will be less than the mentioned value.

- **Air gap**
  - The air gap is 2.5 µm and it is determined by the process and is not tuned.

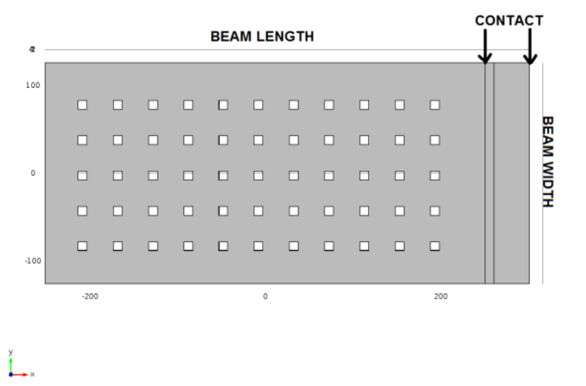

Figure 31. Top view of the beam showing its shape and dimensions

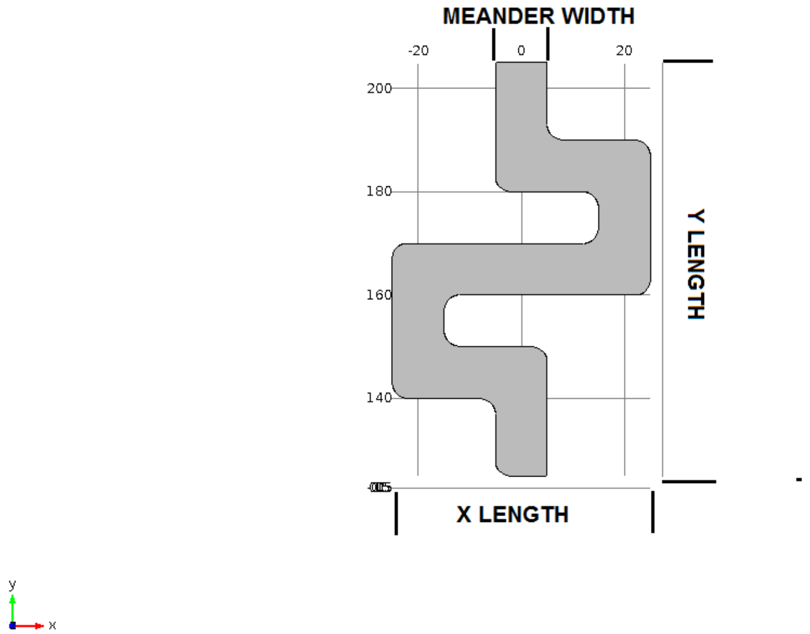

Figure 32. Top view of the Meander showing its shape and dimensions

7.4 Selection of Materials

7.4.1 Substrate

The substrate's material is alumina which is the "UW MEMS" standard process substrate.

7.4.2 Beam

The beam's material is gold as it is included in the actuation process so a metal is needed and gold is typically used for actuation.

7.4.3 Electrodes

Made of gold also due to their high conductivity.

7.4.4 Contact

Made of gold, typically gold is the most suitable material for the contacts, as it has good conductivity, high chemical resistance to corrosion and contamination.

7.4.5 Isolation

A layer of Silicon Nitride is used between the beam and the contact to isolate the DC bias for actuation from the signal path.

7.5 Principle of operation

The switch is based on two distinct states, the on state and the off state.

It is inspired by the seesaw structure exhibiting similar dynamics.

7.5.1 Off state

The left electrode is controlled to operate in this state causing the beam to bend in the anticlockwise direction moving the left part of the beam downwards and the right one upwards.

In that case the contact is moved upwards away from the RF lines to introduce very high isolation as will be shown in Results section.

Insulator is placed under the left part of the beam as a stopper to prevent short circuit between beam and electrode which both electrically represents two terminals of the battery.

7.5.2 ON state

The right electrode is controlled to operate in this state causing the beam to bend in the clockwise direction moving the right part of the beam downwards and the left one upwards as shown in Figure 33 resulting in metal contact between part of the beam and each line.

The metal contact between the two RF lines will result in a very low insertion loss as will be shown in Results section.

Insulator is placed under the right part of the beam as a stopper to prevent short circuit between beam and electrode which both electrically represents two terminals of the battery.

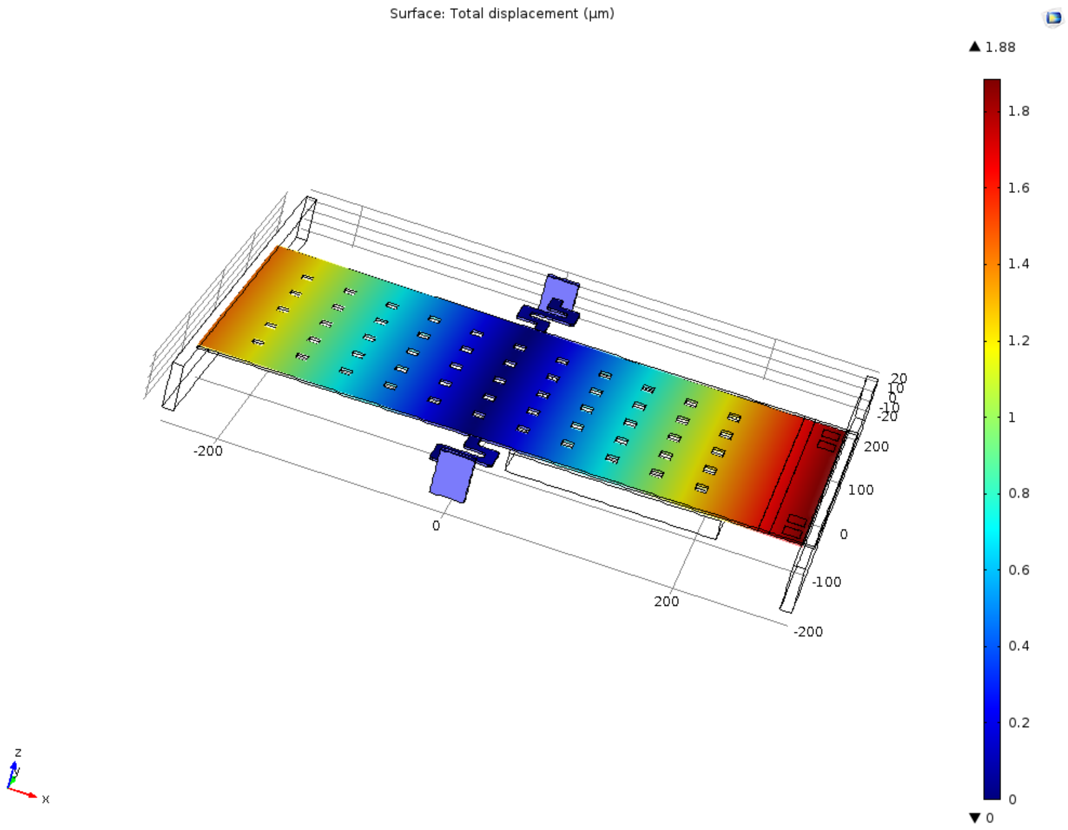

Figure 33. Bending of the beam with right electrode actuation

7.6 Results

All simulations and results are done using COMSOL MULTIPHYSICS platform.

7.6.1 Mechanical

7.6.1.1 Displacement

The beam reaches a displacement of 1.88 µm as in Figure 33.

The air gap is 2.5 µm between the beam and lines, and while having dimples in the contact having height of 1 µm resulting in a gap of 1.5 µm between the dimple and the line.

Therefore, having 1.88 µm displacement means that the dimples reach the line causing metal contact and additional 0.33 µm is converted into contact force which decreases contact resistance to enhance the insertion loss.

7.6.1.2 Stress

The stress along the surface of the structure has a peak in the range of MPascal and the average is much less than that value as shown in Figure 34.

7.6.1.3 Structure's Natural frequencies

Structure's first 12 natural frequencies in ascending order around zero Hz as follows:

- 1.4156 KHz
- 5.4689 KHz
- 14.399 KHz
- 18.465 KHz
- 19.306 KHz
- 43.147 KHz
- 43.779 KHz
- 46.320 KHz
- 49.533 KHz
- 65.571 KHz
- 72.151 KHz
- 75.018 KHz

7.6.2 RF performance

The range of frequencies the switch designed for is the mobile band (DC-6 GHz).

7.6.2.1 Isolation

The required isolation (>30 dB) is satisfied along the range as shown in Figure 35.

7.6.2.2 Insertion loss

The required IL (<.1 dB) is satisfied along the range as shown in Figure 36.

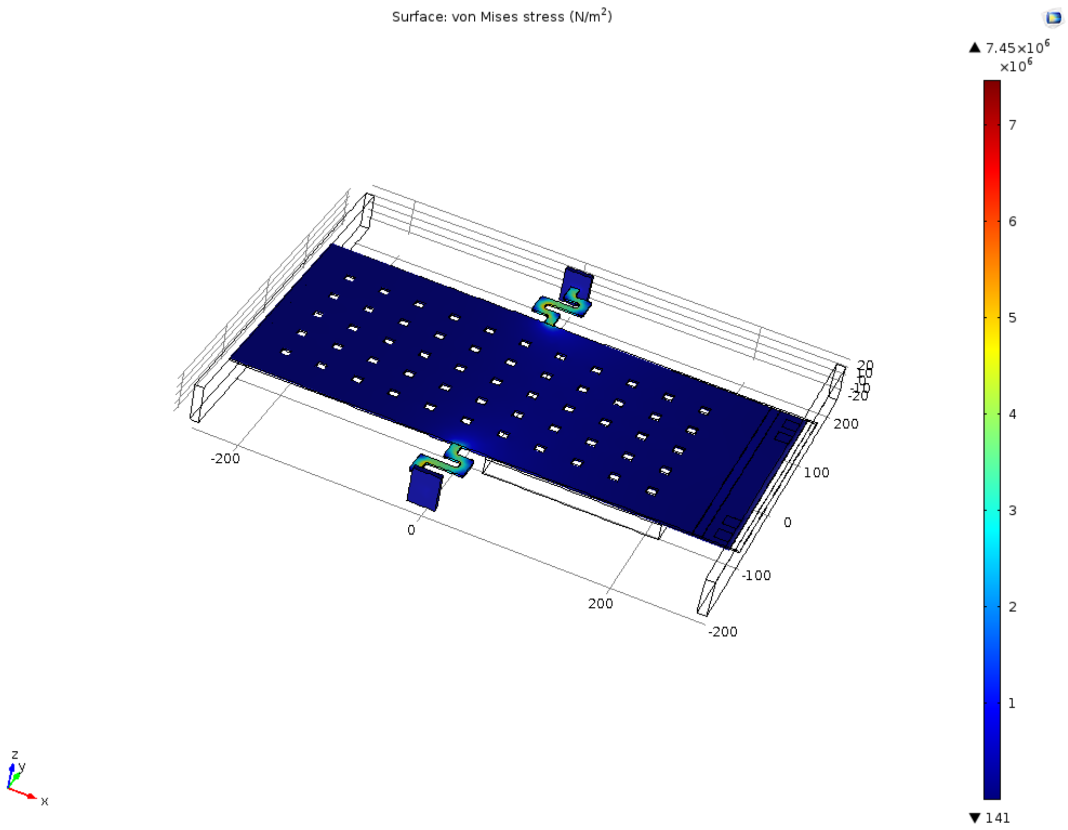

Figure 34. Stress distribution along the surface of the switch

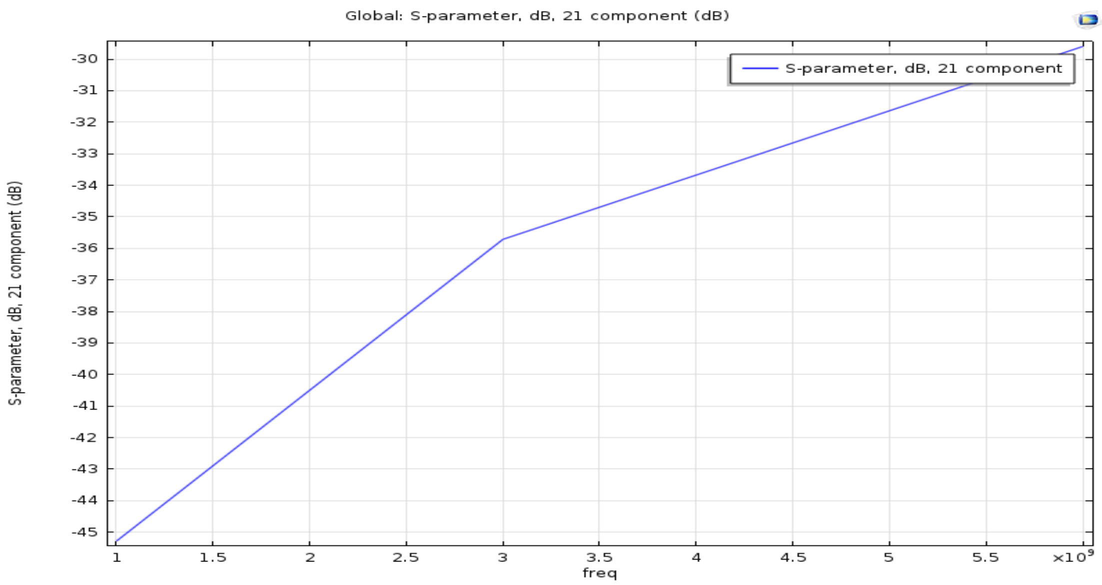

Figure 35. Isolation curve along the range of operating frequencies

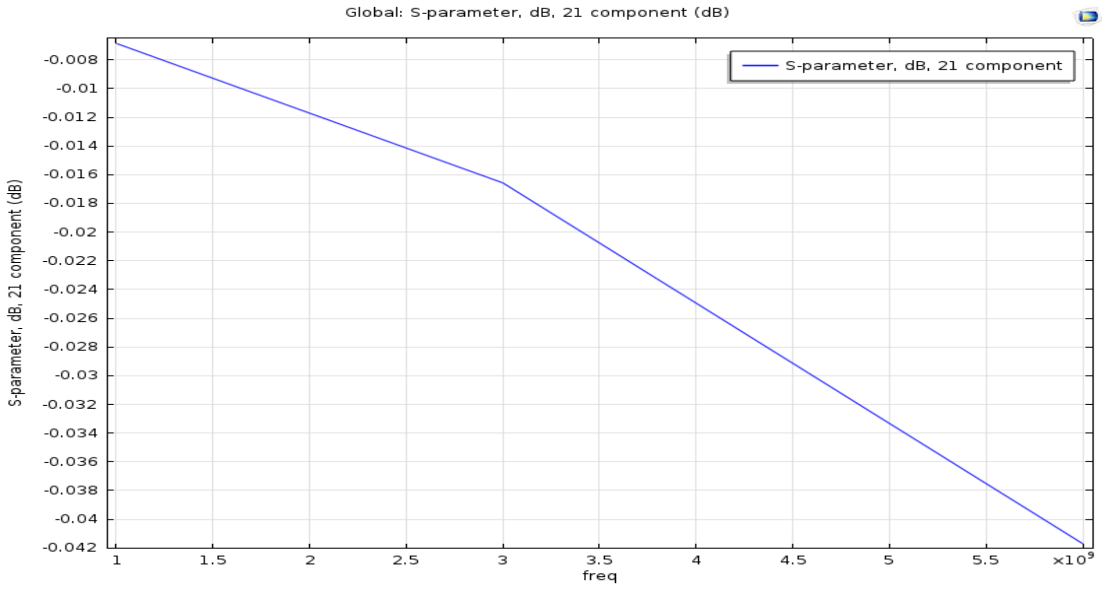

Figure 36. Insertion loss curve along the range of operating frequencies

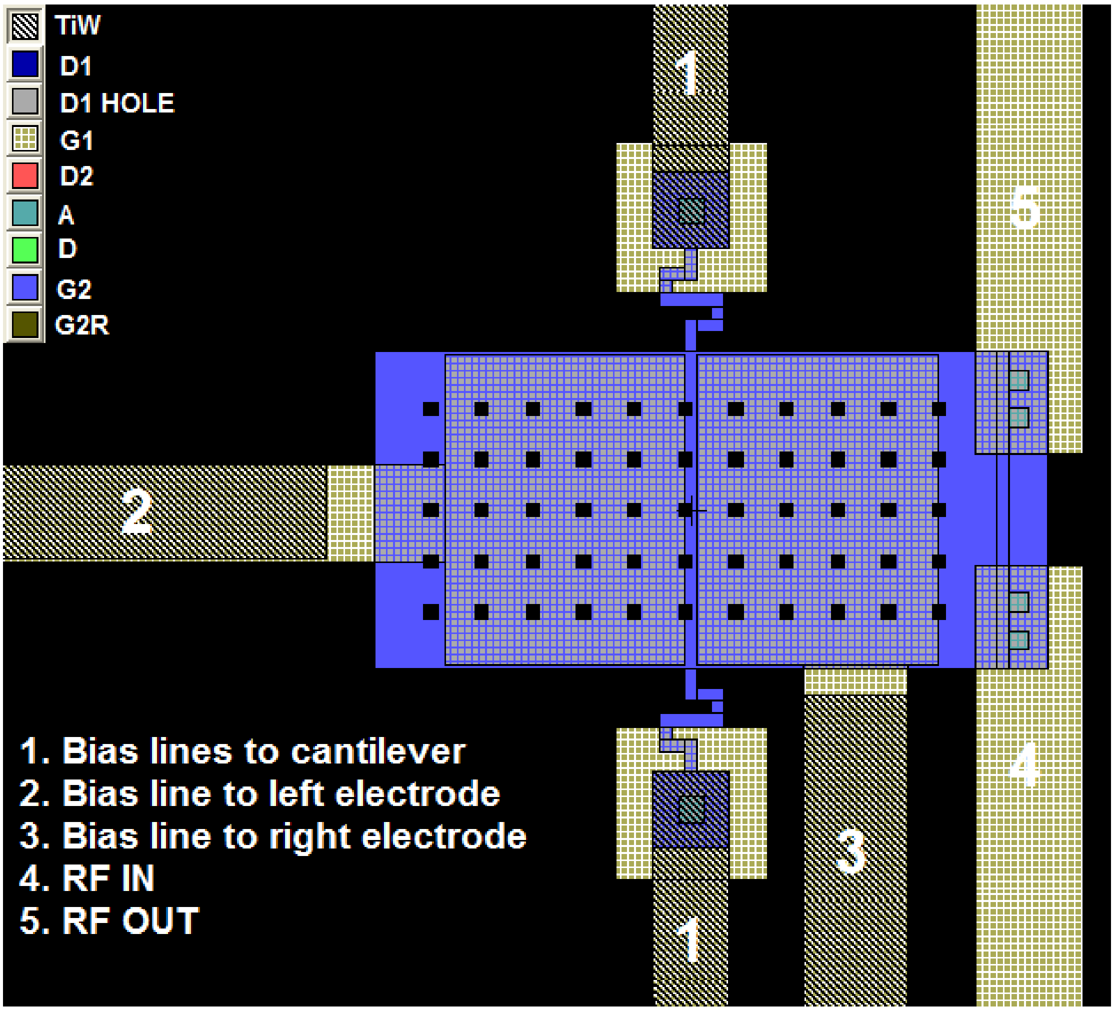

Figure 37. Layout of the RF switch second design

7.7 Layout

The layout represented in Figure 37 is the layout of the previous design built based on UW MEMS [30] process as mentioned with details in Appendix B: UW-MEMS Layout Design Guidelines taking into consideration the design rules and the fabrication steps.

For trying to understand this layout, UW MEMS Handbook should be taken into consideration.

7.8 Summary & Conclusion

The proposed second design presents an RF MEMS switch which is voltage compatible with mobile batteries (3.3 v) operating in the range of DC-6Ghz to be integrated with a reconfigurable microstrip antenna, the switch resulted in excellent performance in terms of insertion loss (.042 dB at 6 Ghz), isolation (30 dB at 6 Ghz), low actuation voltage (3.3 v), low level of stress (Maximum of 7.4 MN/m^2) that's compatible with the UW-MEMS process. Further Investigations needs to be done before fabrications such as contact analysis and switch time response and after fabrication to test switch life cycles, power handling, power consumption and simulated specifications (verify simulated specifications like Isolation, IL,…etc.).

Chapter 8: **Conclusion**

In this thesis, two low voltage mobile compatible RF MEMS switches were introduced which showed excellent RF performance. The first proposed design was in compatible with current standard fabrication processes but had novel design. The second proposed design is designed to be compatible with UW-MEMS fabrication process.

Future work mainly include sending layout for the second proposed design to be fabricated, and testing it after fabrication to verify its specification and do furthers tests on switch reliability.

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Appendix A: Tutorial on COMSOL Multiphysics Platform

COMSOL is a Multiphysics platform, which we used to do all our simulations.

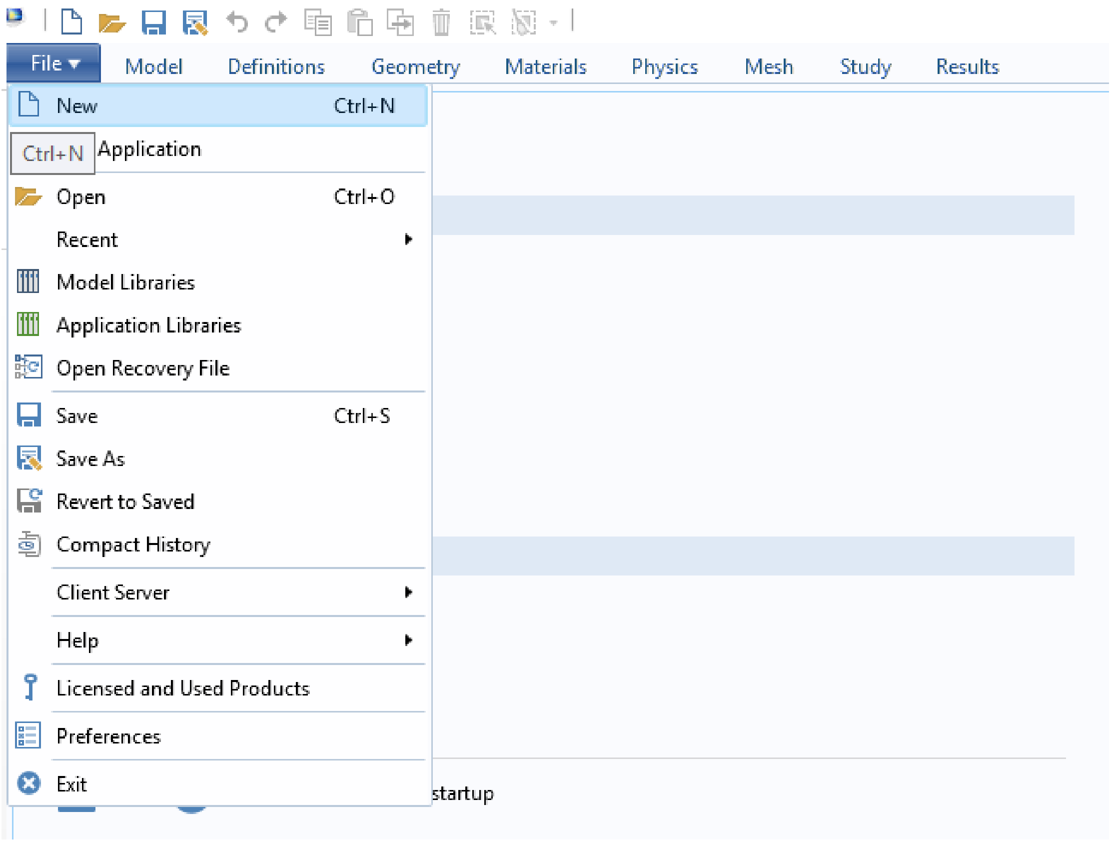
In this appendix, we show how to do the following using COMSOL step by step:

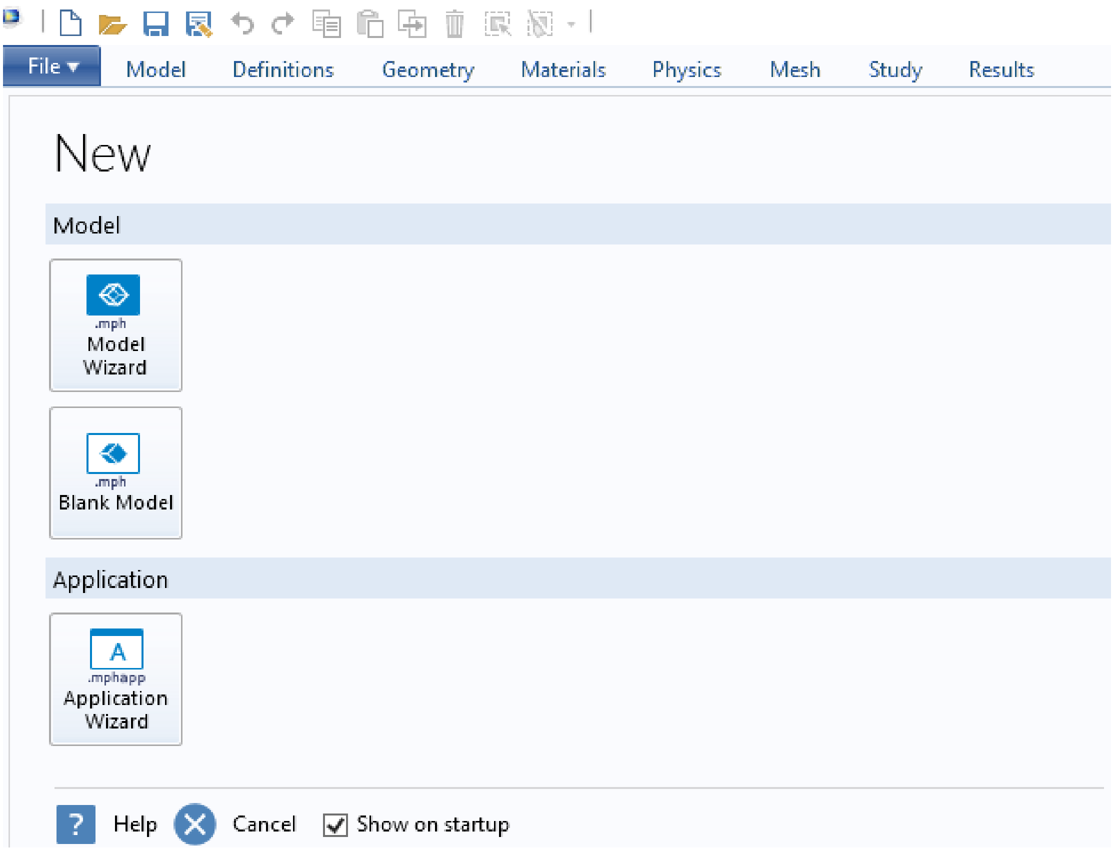
1- Program Setup (Initialization)
2- Defining Parameters
3- Building Geometry
4- Defining Materials
5- Defining Physics
6- Defining Mesh
7- Configuring Study
8- Configuring Results

We first start with an example on a very simple electrostatic actuated RF MEMS Switch. (Most of the following steps apply on other models)

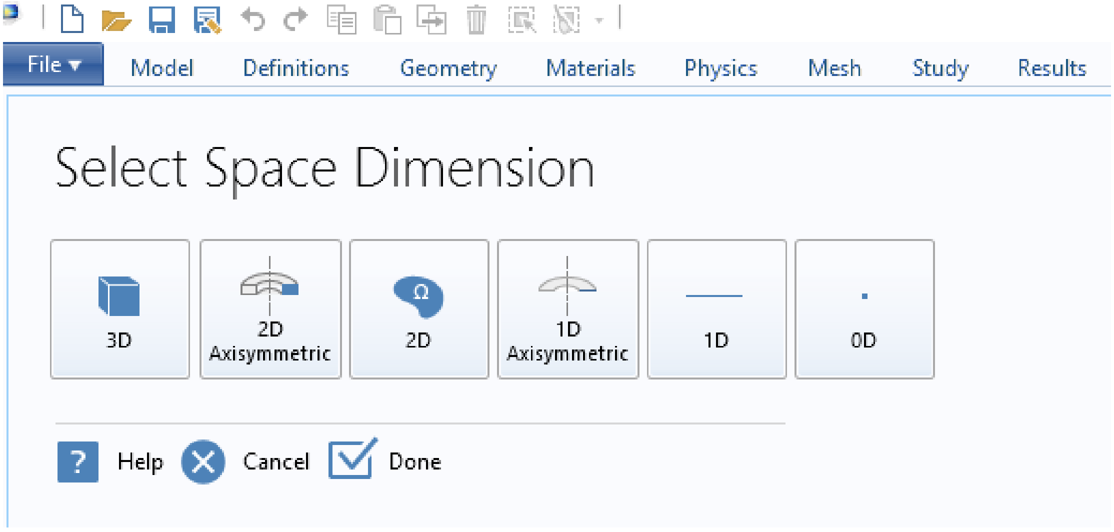
1. Program Setup (Initialization)

1 We start with choosing File>New, from Model choose Model Wizard


File
Model
Definitions
Geometry
Materials
Physics
Mesh
Study
Results
New Ctrl+N
Ctrl+N
Application
Open Ctrl+O
Recent
Model Libraries
Application Libraries
Open Recovery File
Save Ctrl+S
Save As
Revert to Saved
Compact History
Client Server
Help
Licensed and Used Products
Preferences
Exit
startup

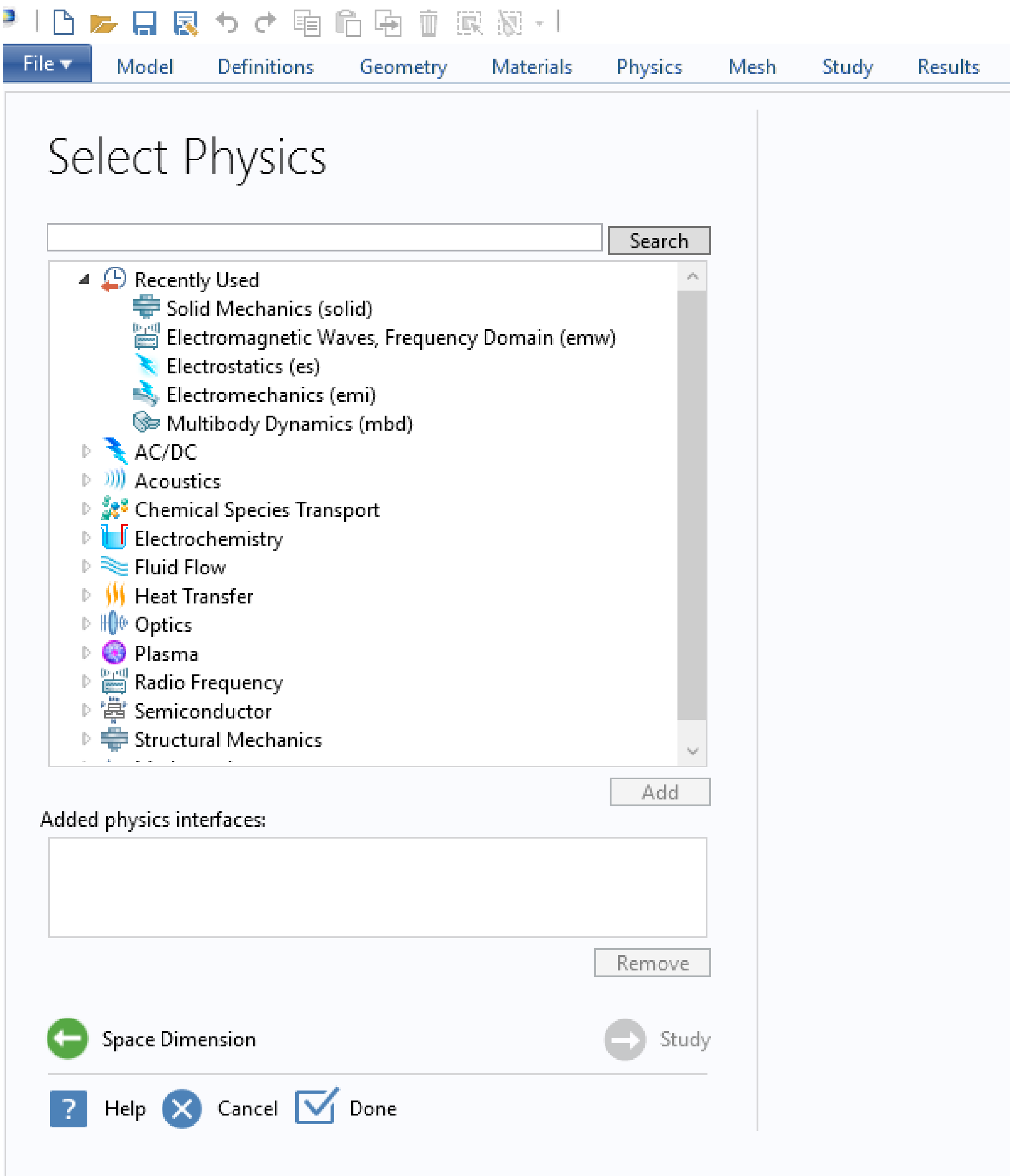

File
Model
Definitions
Geometry
Materials
Physics
Mesh
Study
Results
New
Model
.mph
Model Wizard
.mph
Blank Model
Application
A
.mphapp
Application Wizard
Help
Cancel
Show on startup

2 In the Model Wizard window, click 3D.



3 In the Select physics tree, select Structural Mechanics>Electromechanics (emi).

4 Then click Add. (If you need to add more physics to your model, you can add it from here or later on from inside the model)

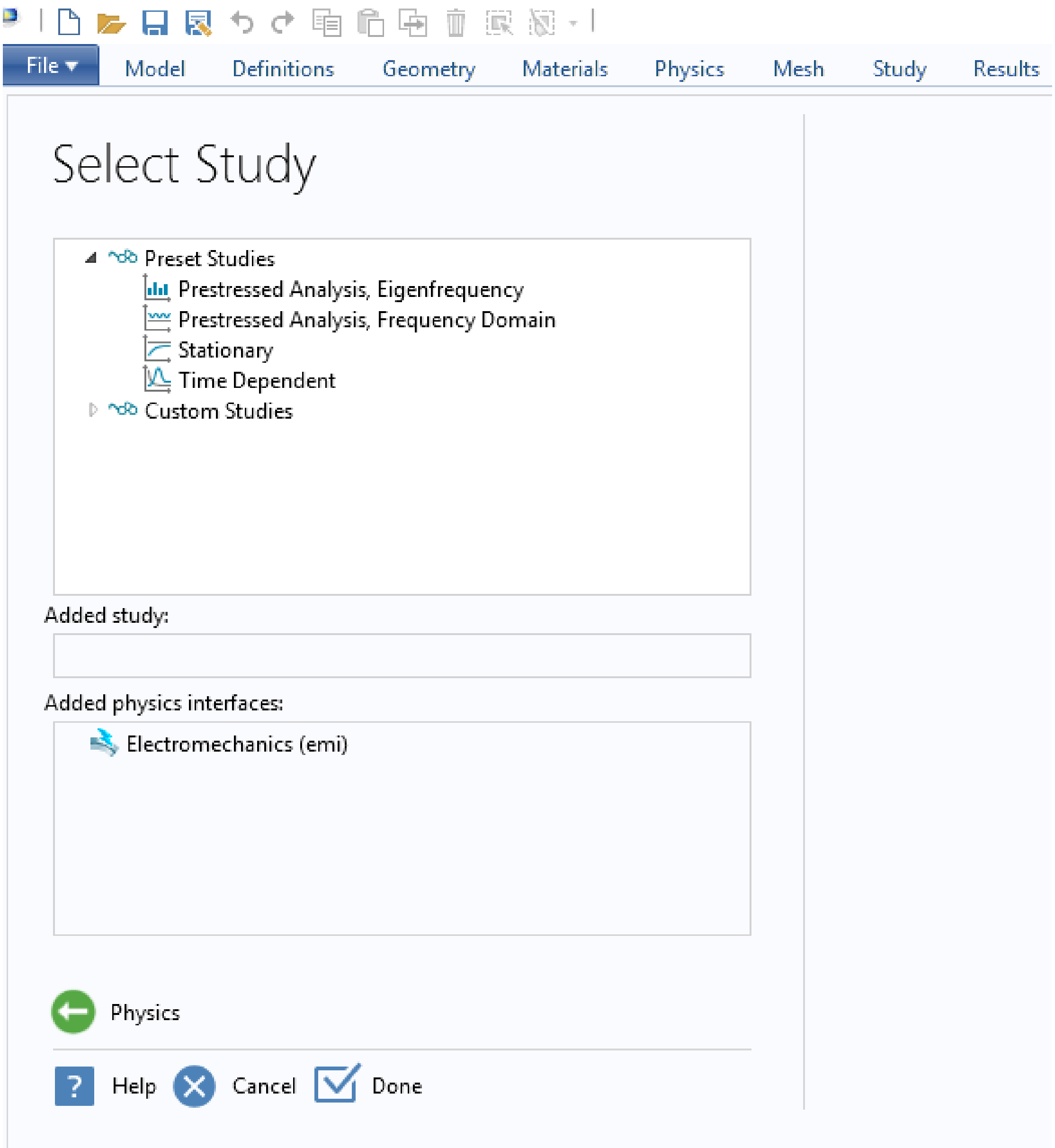


5 Click Study.

6 In the Select study tree, select Preset Studies>Stationary.

7 Click Done.

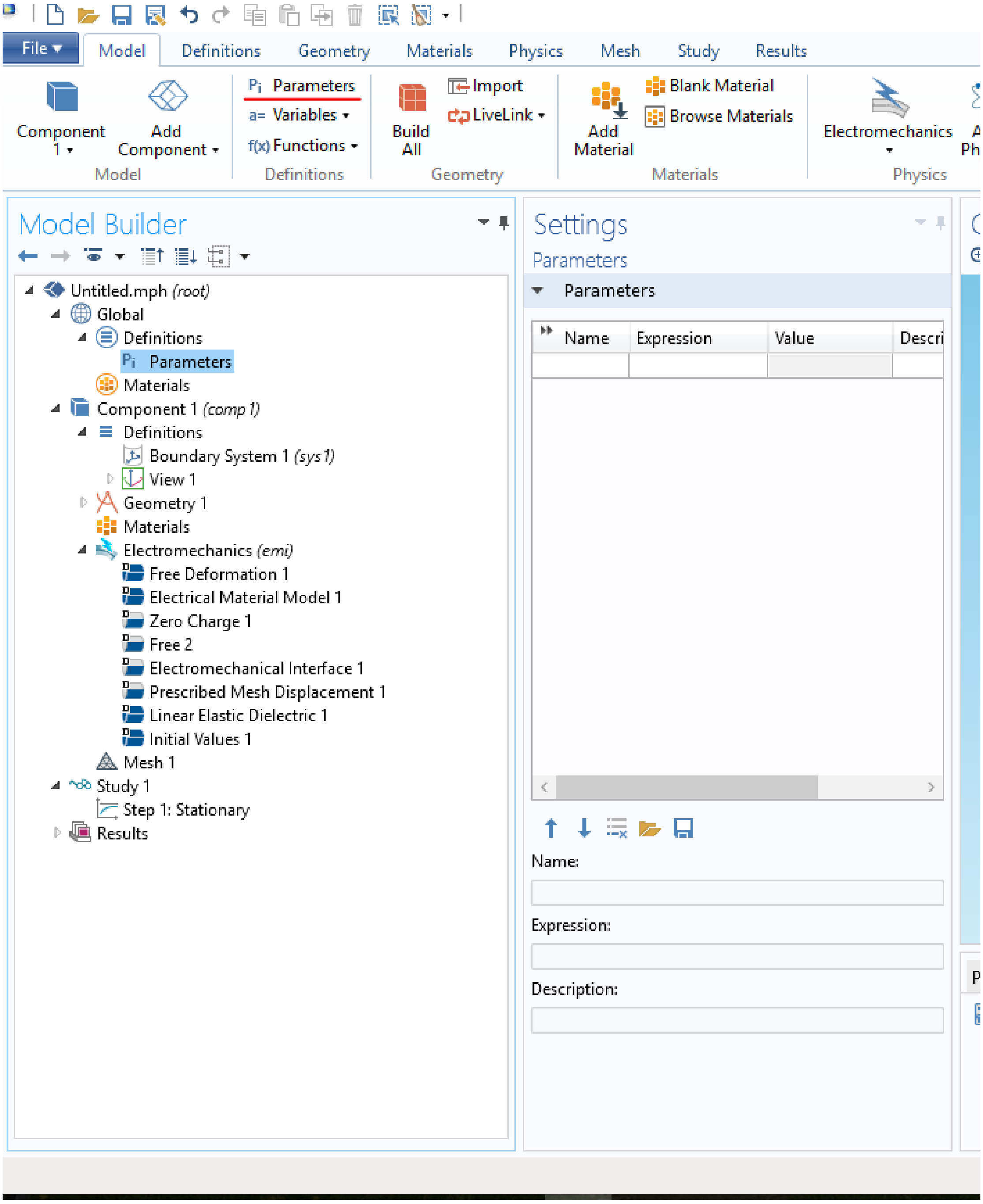
Note: here in this example we chose Stationary study, as we want to see the steady state result not the response with time (Time Dependent), with frequency (Frequency Domain),…etc.


File
Model
Definitions
Geometry
Materials
Physics
Mesh
Study
Results
Select Study
Preset Studies
Prestressed Analysis, Eigenfrequency
Prestressed Analysis, Frequency Domain
Stationary
Time Dependent
Custom Studies
Added study:
Added physics interfaces:
Electromechanics (emi)
Physics
Help
Cancel
Done

2. Defining Parameters

1 On the Model toolbar, click Parameters.

2 In the Settings window for Parameters, locate the Parameters section.



3 In the table, enter the following settings:

Name	Expression	Value	Description
Vdc	100[V]	100 V	Actuation Voltage
L	100		Cantilever Length
W	100		Cantilever Width

Notes:

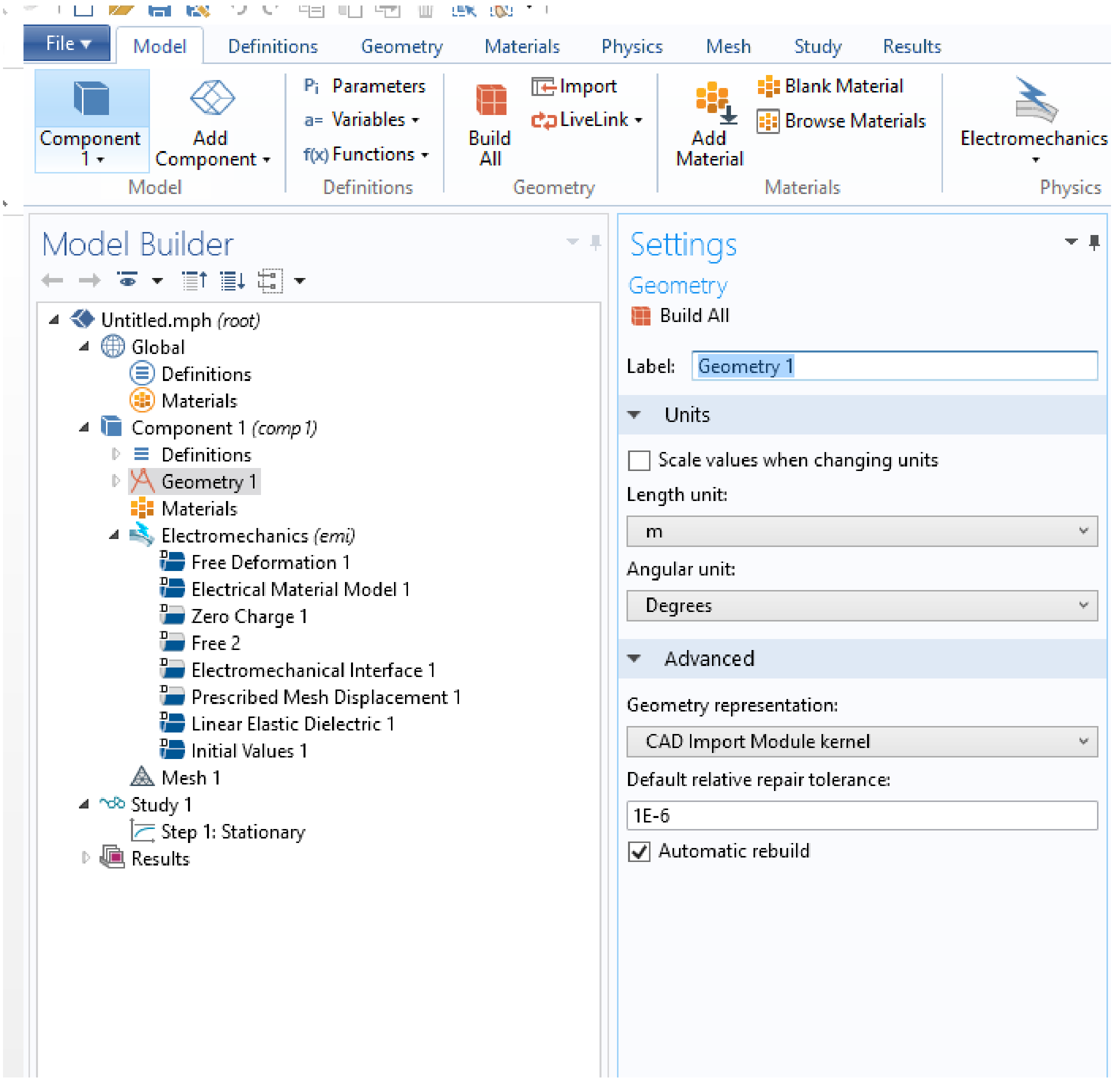
- You can enter the value unit-less, or with you unit if you are planning to use it in a defined unit entry (i.e. enter "L" in Length Entry of a certain block in Geometry, any value you enter is already defined in µm).
- The unit you enter between [m], i.e. [nm] (for nano meter) it overrides what's in your model, meaning the value is going to be in nm not in nm multiplied by 10^{-6} (as you defined your model in µm)
- The description you enter is very useful, first as a reminder for you (especially when you have a lot of parameters, as if you build a certain model and came to check it after i.e. a month, from the description you can have a clue each value refer to what). Also it's useful if you are working in a team (in most cases) and need to share your models with them (you need to make it user-friendly as possible).
- Here we defined Vdc which we will use in Physics part, L & W in the Geometry. But usually in Geometry you need to add more than just L & W (this is done in sake of the simplicity of the example), in practice you try to transform all your geometry inputs into parameters, this sometime can take a considerate time and effort but it's very useful (and worth the time spent) if you are planning to either keep making changes to your model (i.e. to test performance of your model) or you need to do a parametric sweep (you need a defined parameter to sweep it).

3. Building Geometry

1 In the Model Builder window, under Component 1 (comp1) click Geometry 1.

2 In the Settings window for Geometry, locate the Units section.

3 From the Length unit list, choose µm. (As we are making a MEMS structure in µm range). You can also change Angular unit if you are planning to work with angles in building your geometry.



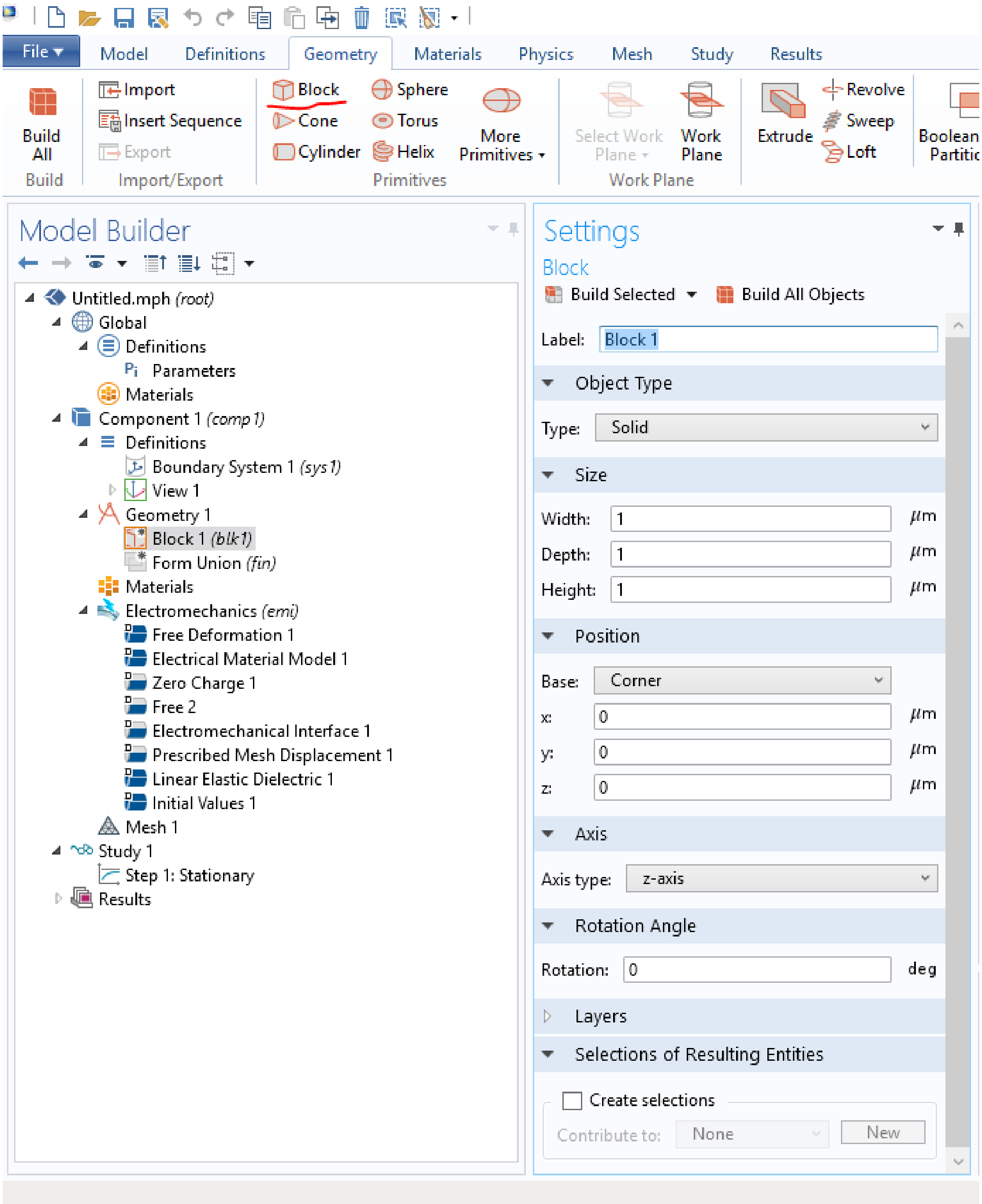
In Geometry 1, we begin to build our model. As we are building a simple RF MEMS Switch we need to make the following components:

1- Anchor
2- Cantilever
3- Electrode

You may think that we need the RF ports, but for simplification we can ignore them as they won't affect the displacement of the cantilever (they can have effect if you are doing contact analysis, which is out of scope of this example).

Steps:

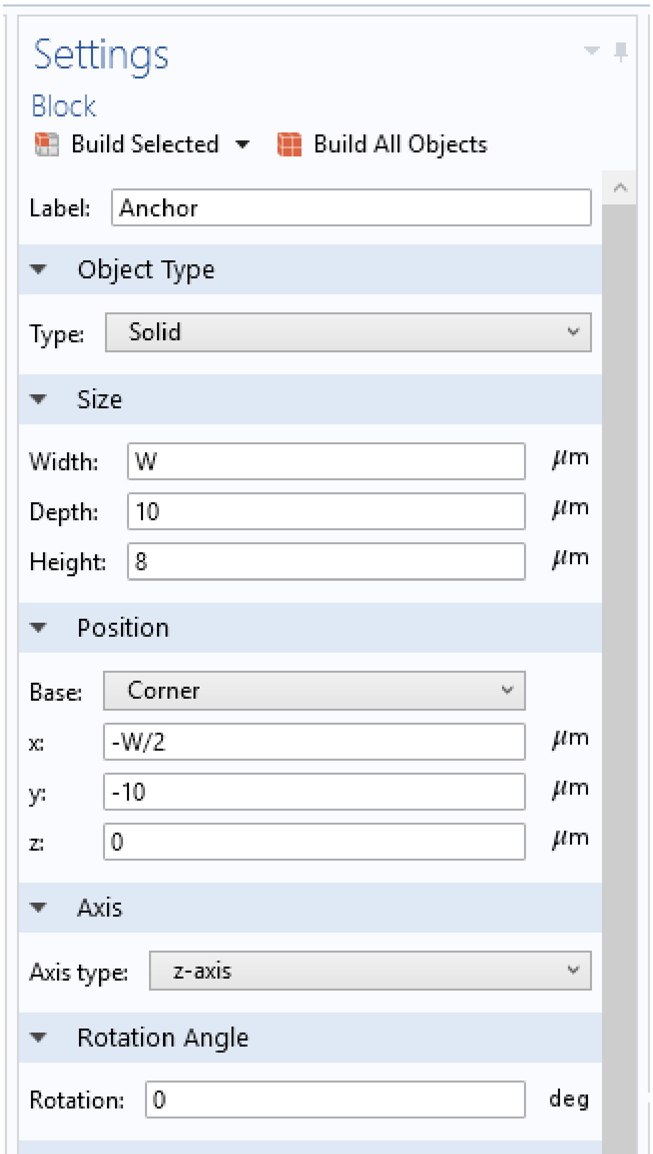
1 On the Geometry toolbar, click on block from Primitives section. (General Note: you can always work either from the toolbar in the upper section in COMSOL window, or you can right click on geometry 1 and click on block)



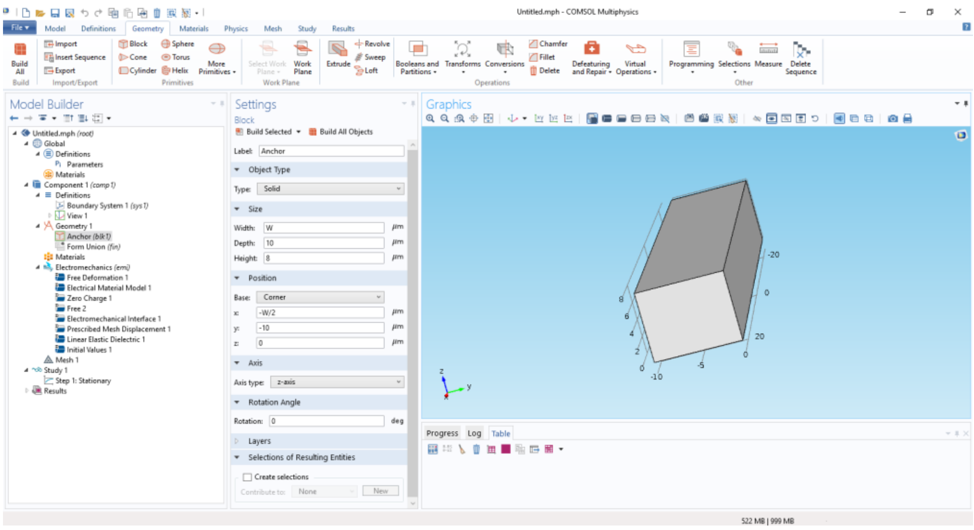
Again as we mentioned the advantage of writing parameters description it's useful to enter meaningful labels for your geometry parts.

2 Enter Anchor in Label box in Block 1 settings

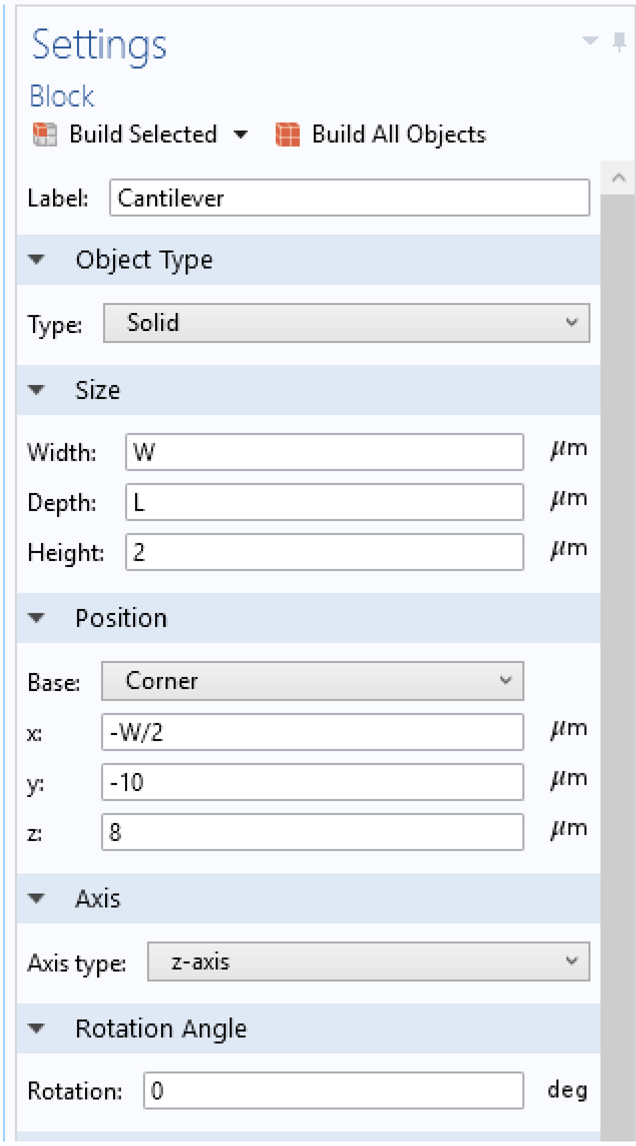
3 Enter the following values

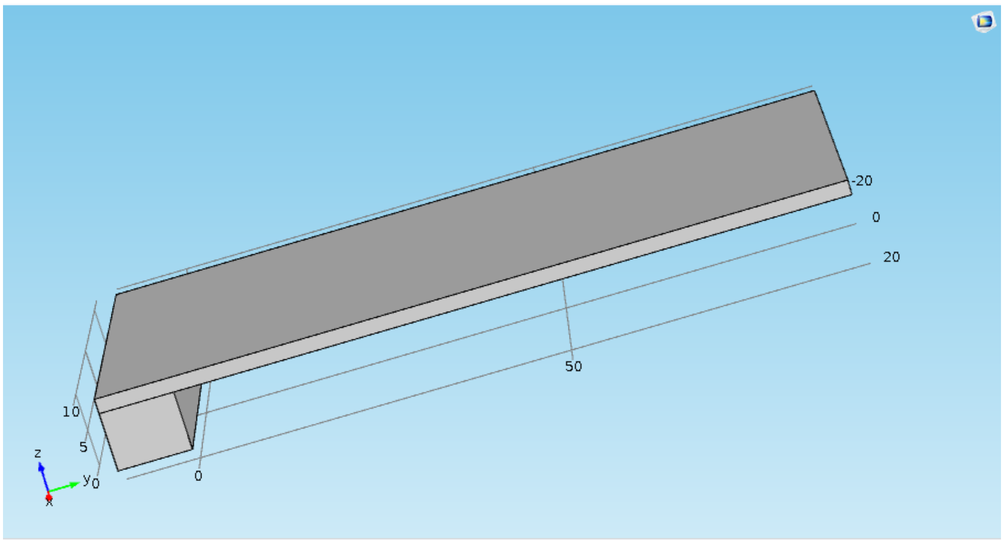


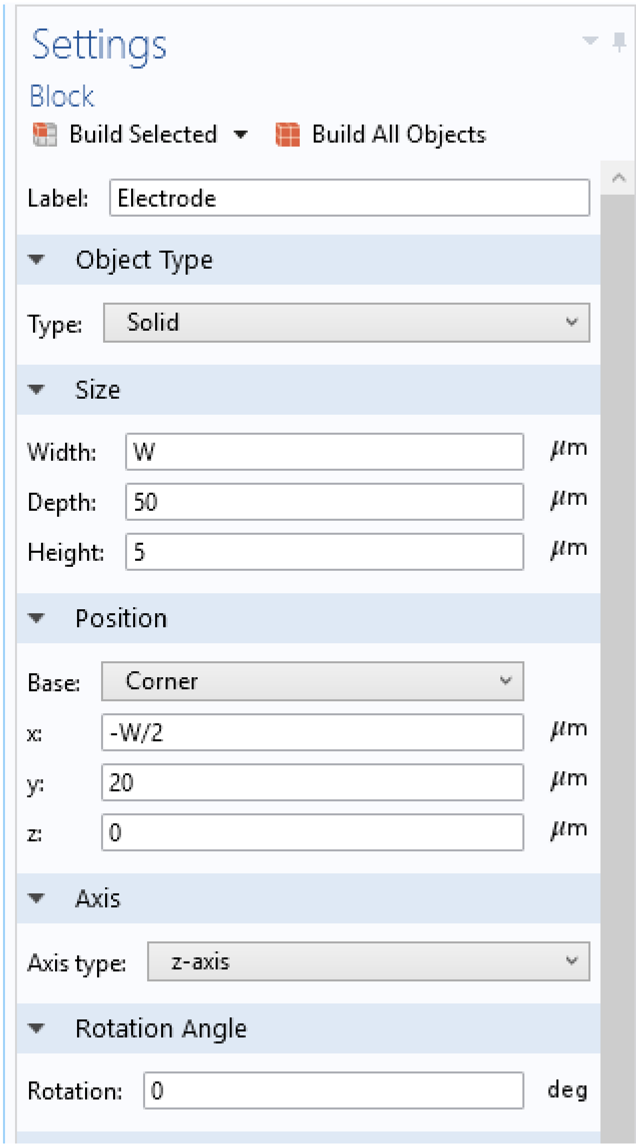
4 Click Build Selected (you should see structure similar to the one below)



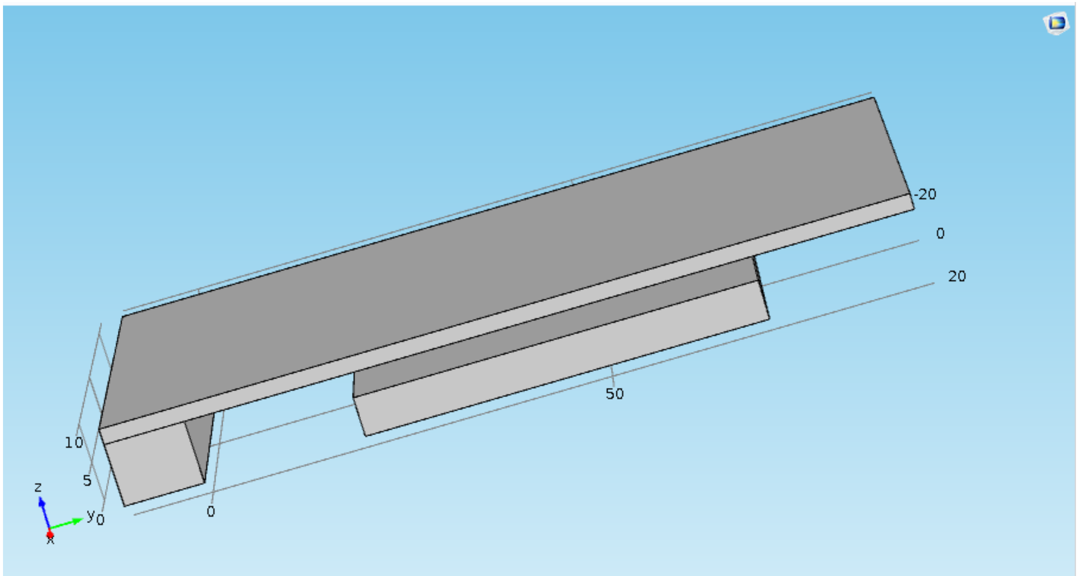
4 Do the same steps for another two blocks with the following Values





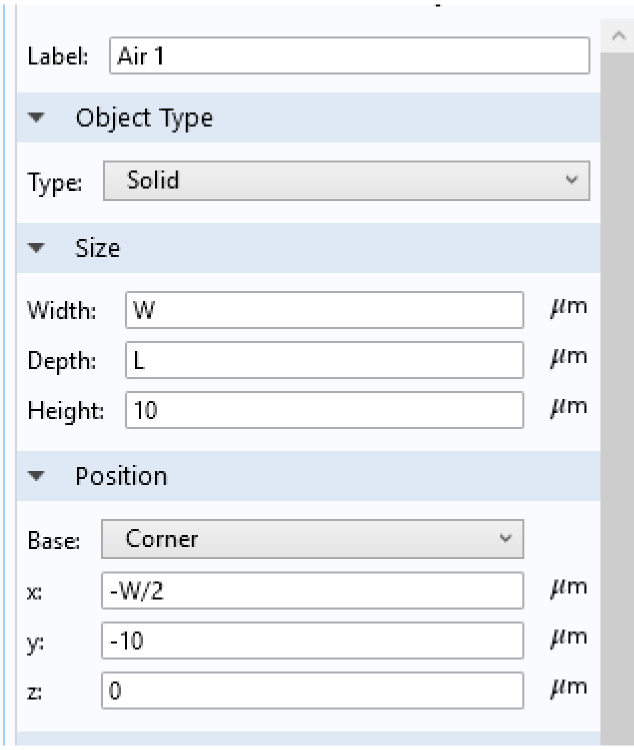


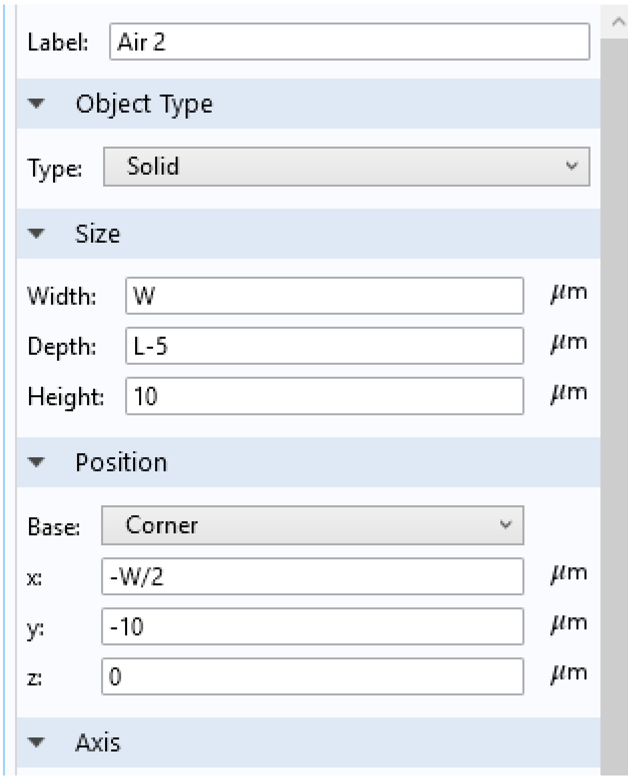
You should have model similar to this:



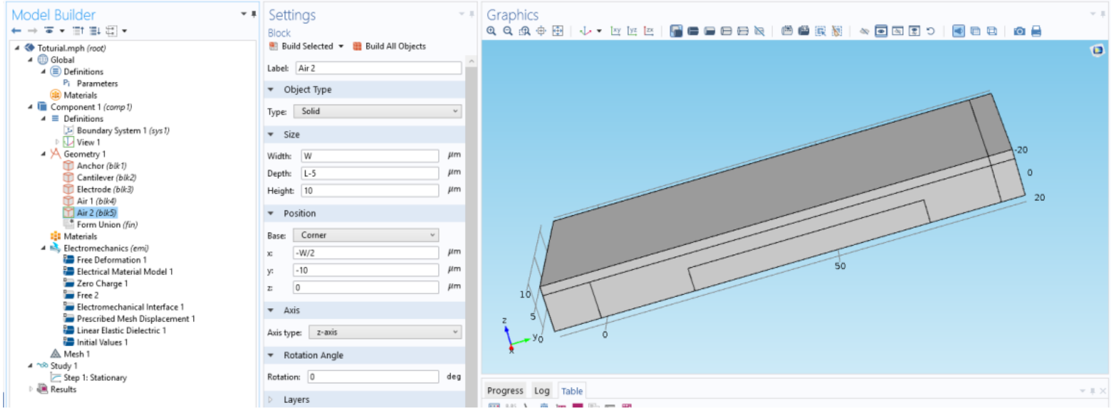
Due to a certain restriction in simulating the structure we need to add two spaces that will going to be filled with air that intersects at the tip of the cantilever.

5 Do the same steps from 1-4 for two new blocks, Air 1 & Air 2

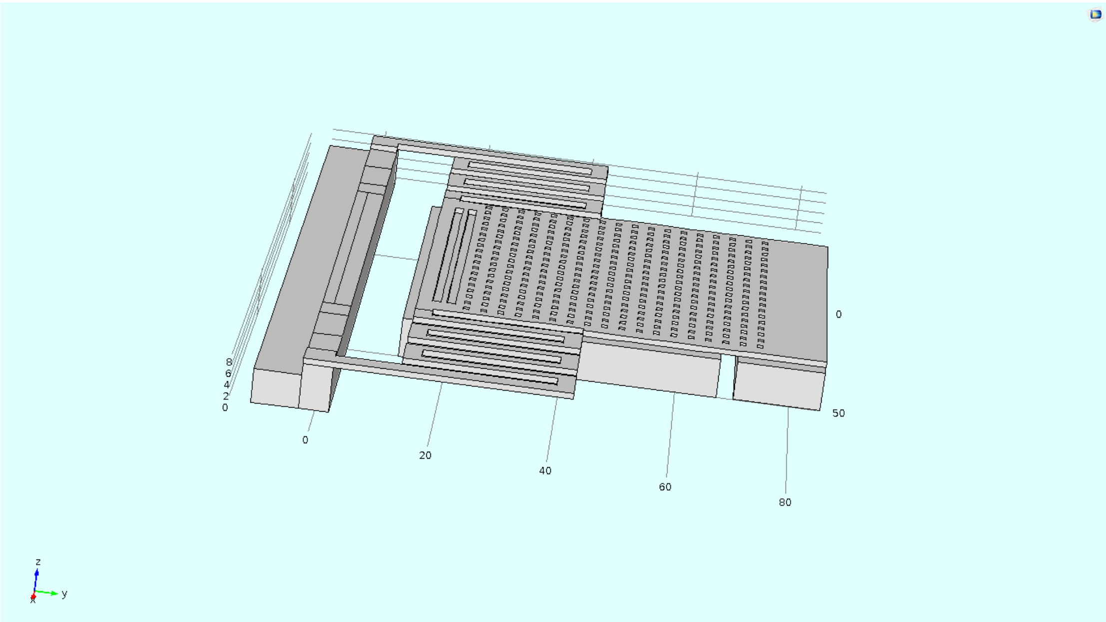




You should have model similar to this:



Here we finished building geometry for our simplified model. You can do more complex structure using different primitives (i.e. Cylinder), use difference function (subtracts parts from each other), Array function to make an array of a certain element (holes in a cantilever), move, copy, mirror or other functions. To reach for example a shape like the one below.



4. Defining Materials

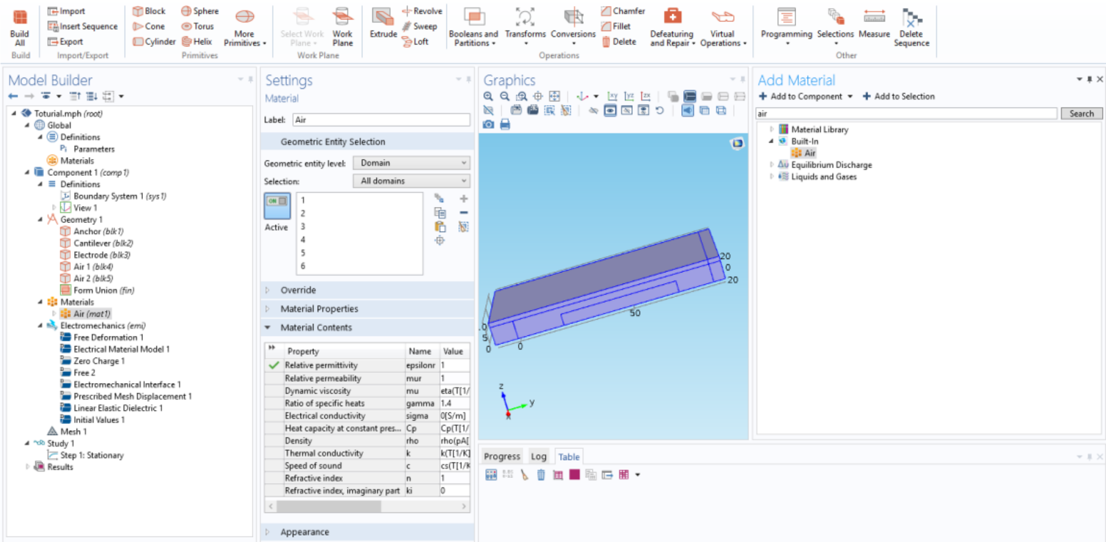
We need to define our structure different materials, in our example, we will build all structure (Anchor-Cantilever-Electrode) from gold, and air in spaces in between.

1 Right click on materials and choose Add Material, a window will open on left part of the window

2 In the search tool bar type air and press search

3 click on Built-in (from the search result) and choose Air

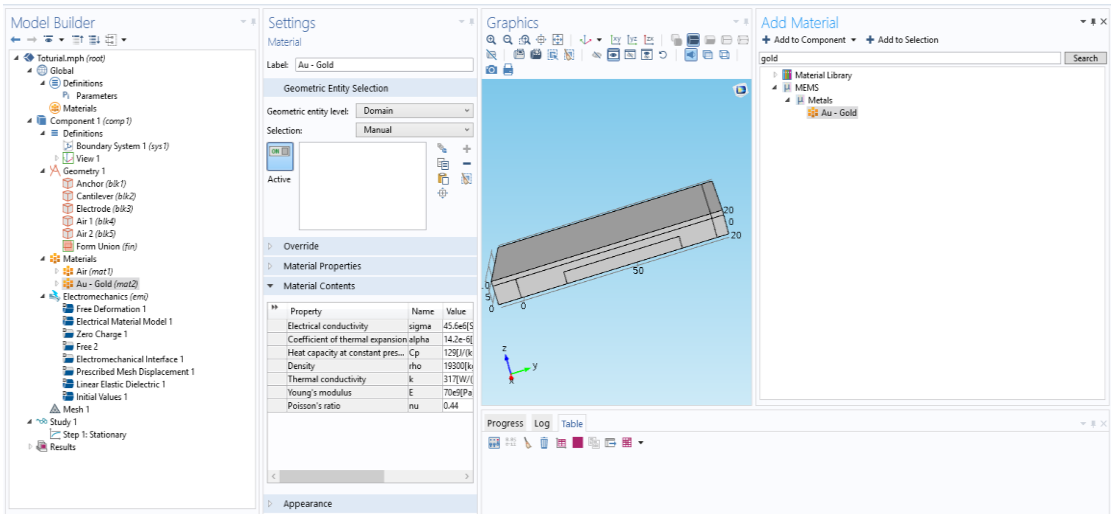
4 Click add to Component



5 In the search tool bar type gold and press search

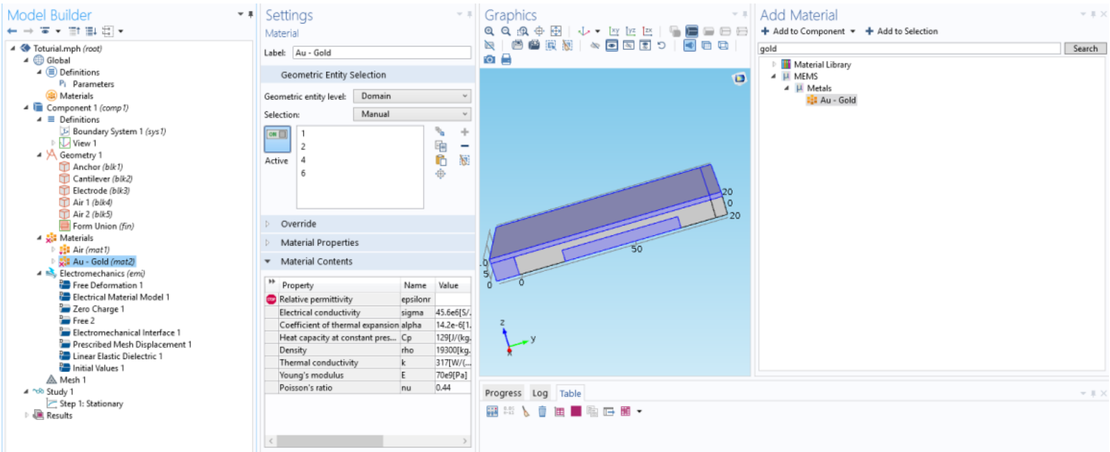
6 Click on MEMS then on Metals then select Au – Gold

7 Click add to Component



You will notice that in Air selection window it add all your geometry to it by default, you simply can choose what parts are gold and the left will be air (if you define parts in the structure to be gold and it's already define in air, it will be overridden and become gold)

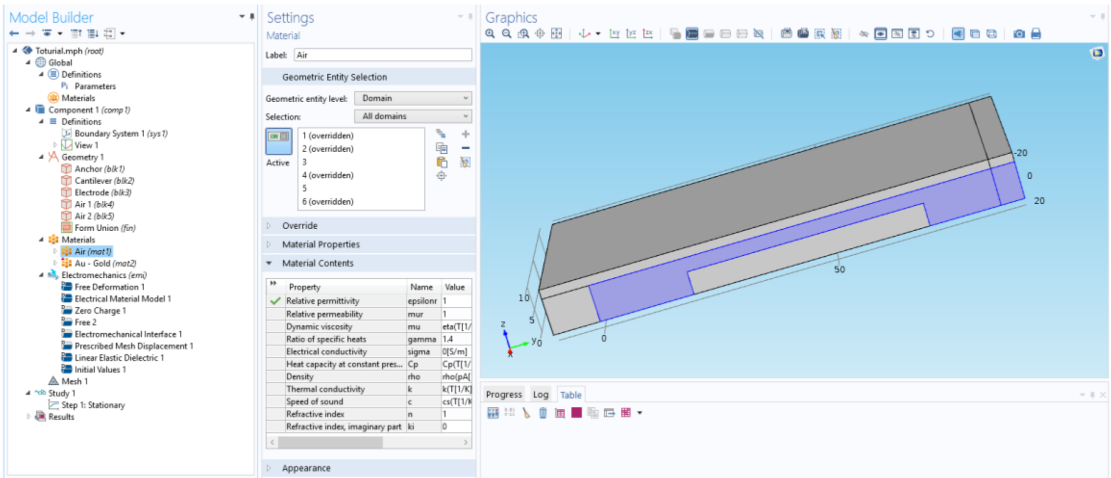
8 Make the selection shown in the figure below (by just clicking on the parts that consists of gold in your model)



You will notice that and error sign appear (X) and if you check material content you find that Relative Permittivity value is not written, for this simulation for gold write 1

9 Enter 1 in Relative Permittivity box in Material Contents

Now close the Add Material window. You will notice if you click on Air from materials section, the air selection appear as in the picture below.



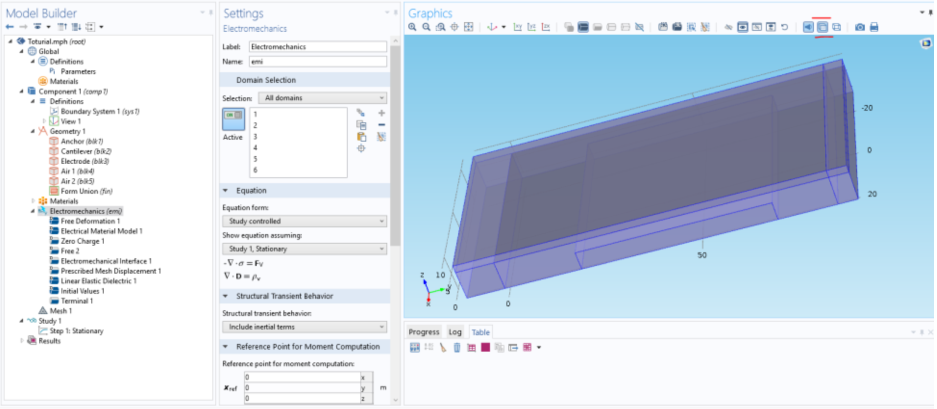
5. Defining Physics

For each physics COMSOL already defines some setup for you, sometimes you need to changes and sometimes not. Here we will only add some other boundaries. For this example we need to define the following:

1- Applied Voltage & Ground
2- Which parts of the structure are free to move
3- Where the fixed point of the moving parts
4- Where the moving mesh parts are and at which axis direction it can move

Steps:

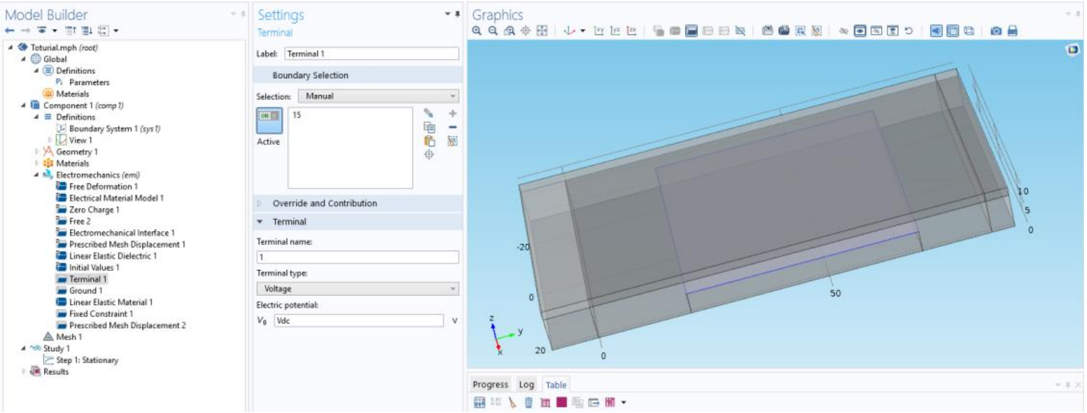
1 To make it easier to select boundaries in the graphic window upper right corner click on Transparency (shown in the picture below)



2 Right click on Electromechanics (emi)>Electrical>Terminal

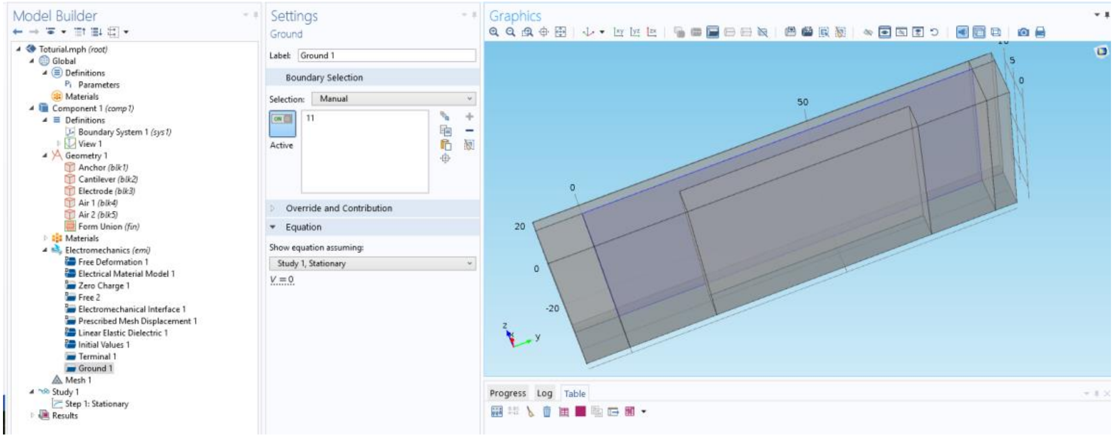
3 Select the Electrode upper face (as in the picture below)

4 Change Terminal Type to Voltage, and Enter Vdc (the parameter we defined before)



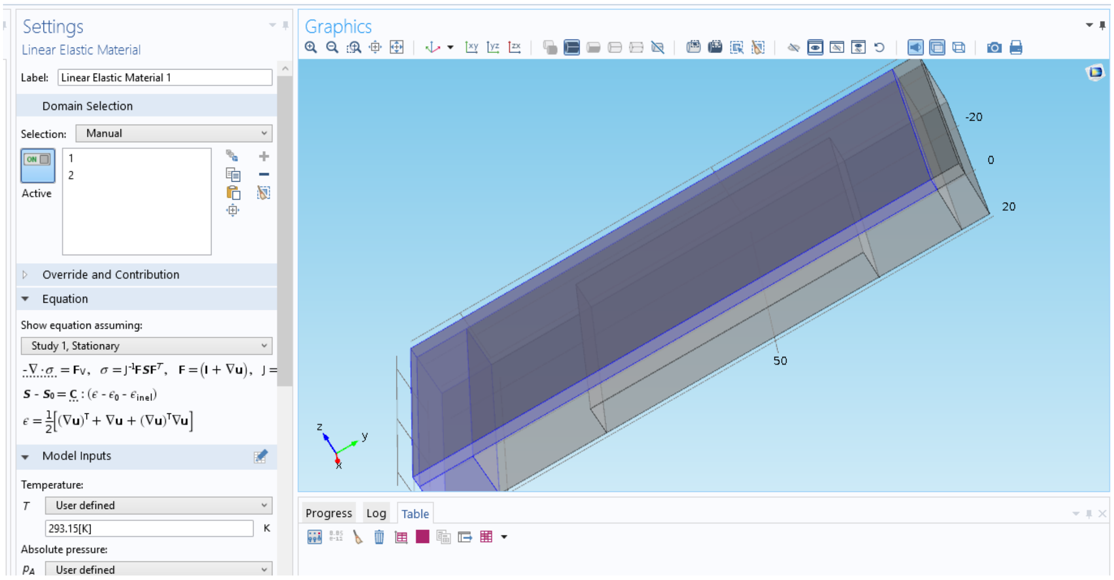
4 Right click on Electromechanics (emi)>Electrical>Ground

5 Select Cantilever lower face (facing the electrode)



6 Right click on Electromechanics (emi)>Linear Elastic Material

7 Select the following parts shown in picture below.



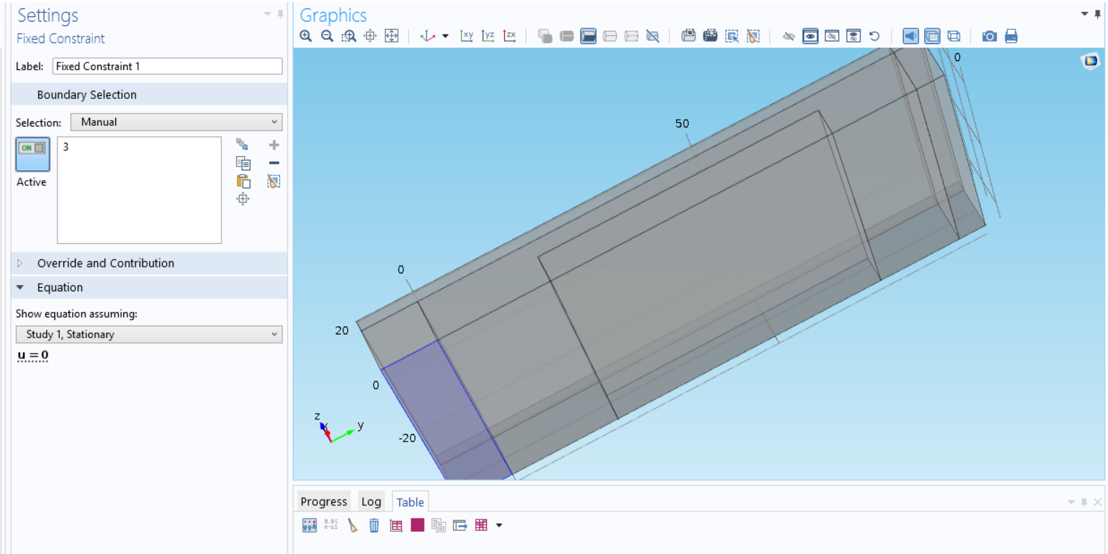
8 Right click on Electromechanics (emi)>Structural>Fixed Constraint

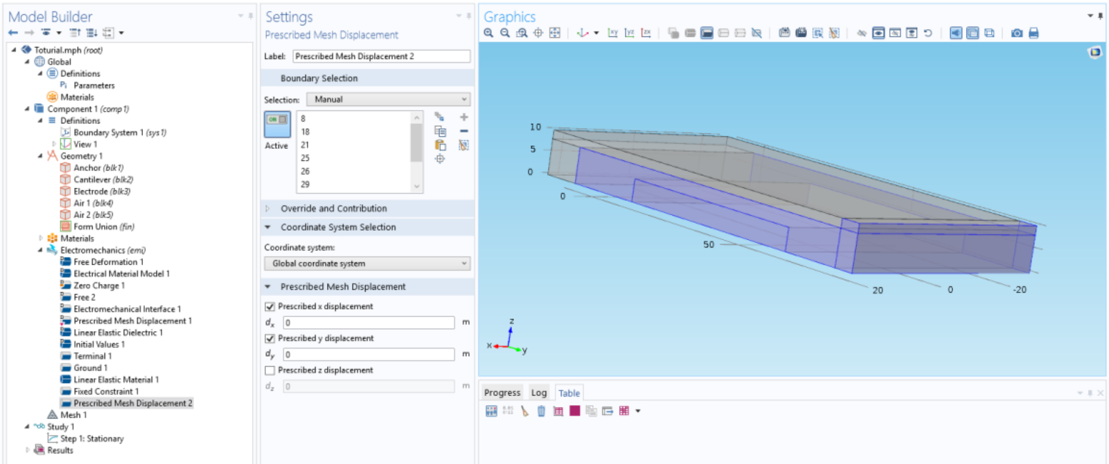
9 Select the Anchor Lower face (as in the picture below)

10 Right click on Electromechanics (emi)>Deformed Mesh> Prescribed Mesh Displacement

11 Select the faces shown below. Note that we select any face that the cantilever is expected to move through.

12 in Prescribed Mesh Displacement 2 (you just created) clear the check box “Prescribed z displacement”

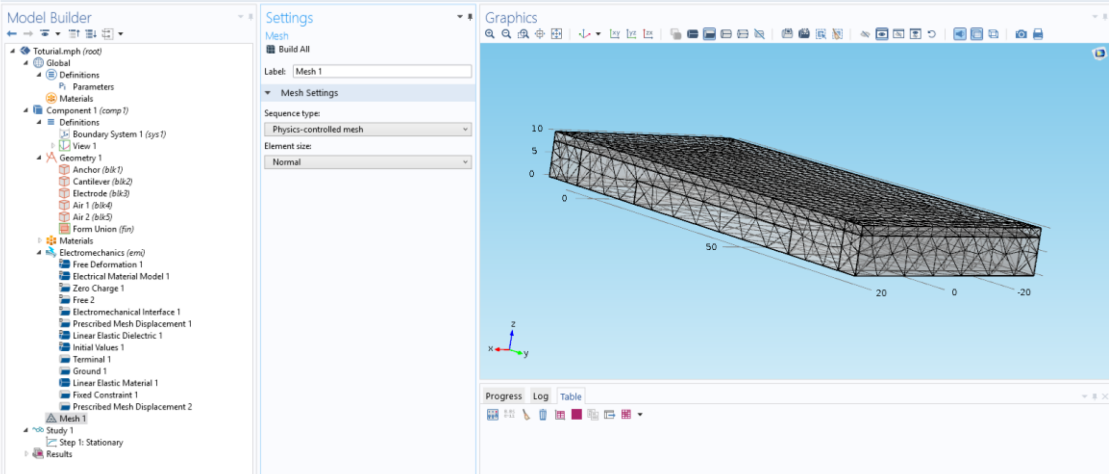




6. Defining Mesh

In any Finite Element Analysis (FEA) Platform, you need to divide your structure into small nodes, to enable the solver to understand the structure and solve the model differential equations. As you increase the Element size you run the simulation faster with less processing power but with low results accuracy (depending on your structure geometry, i.e. if it contains small details than you must use smaller mesh size). Also making the mesh finer (decreasing Element size) would need more simulation time and more processing power (depending on your model it may not even run on your normal laptop). Choosing the mesh is something that comes with experience as you do more simulations on COMSOL you will get the sense of how to choose the optimum mesh for each problem you face.

For this example, just click on Mesh 1 and click on Build All, you should see a figure like the one below.



7. Configuring Study

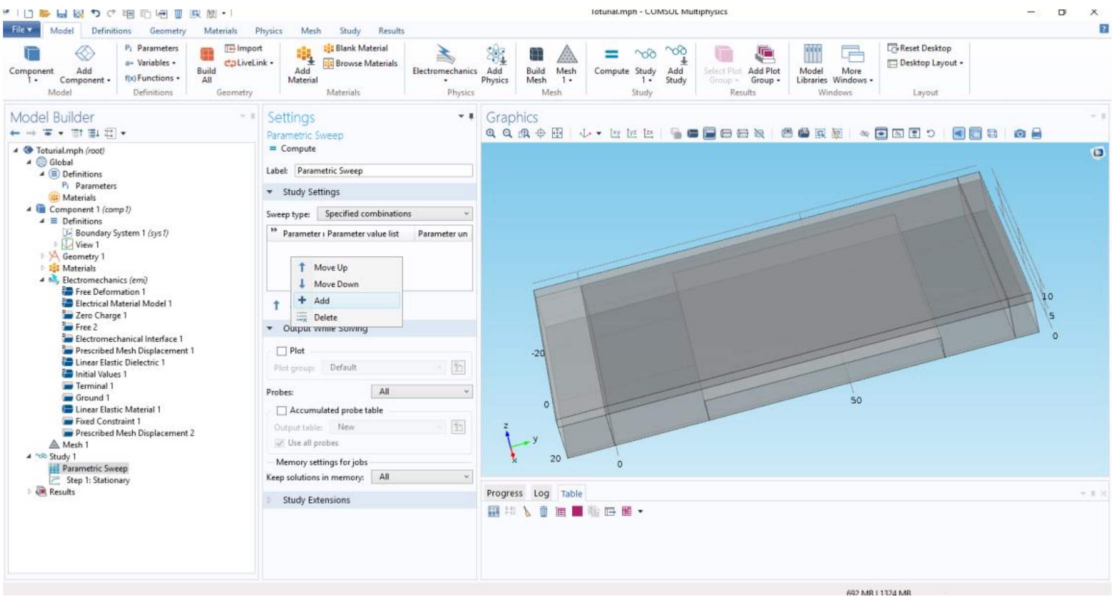
For this example we just click on Compute and wait for the results. Or we can run parametric Sweep over Vdc to see how the structure respond to different voltage values, to run parametric sweep do the following:

1 Right click on Study 1>Parametric Sweep

2 Right click on Parameter List (as shown on the figure below)

3 Choose Add, it Automatically adds Vdc.

4 Enter in the Parameter value box "range(50,50,200)"



Note: range syntax is range(initial value, step, final value). You can also just write specific points as: 50 100 160, without using range function.

Finally, if you want to preview results once they are calculated without waiting for whole parametric simulation to end you can check the plot box in the Output While Solving section.

5 Click Compute

8. Configuring Results

For each physics there are figures that COMSOL plot by defaults, in this example the displacement, potential are plotted.

COMSOL allow plotting another results such as:

1- Stress distribution on the structure, **Steps:**

   I- On the Results toolbar, click on 3D Plot Group.

   II- In the Label box, type Stress.

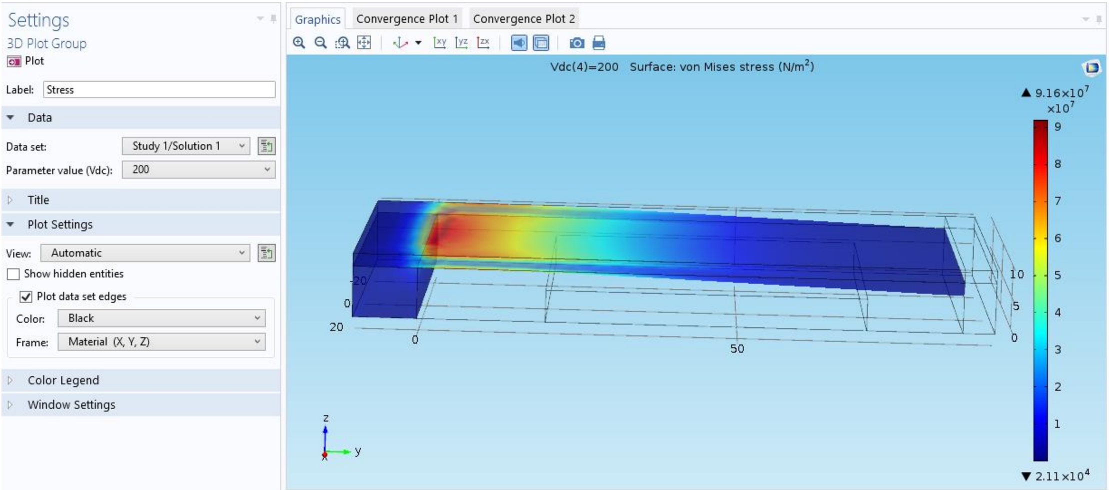
   III- From the Stress toolbar, click on Surface.

   IV- In Surface setting in Expression section, click on Replace Expression (the red and green small arrows).

   V- Choose Model>Component 1>Electromechanics (Solid Mechanics)>Stress>emi.mises - von Mises Stress.

   VI- Click Plot

You should be able to see a figure similar to this



2- A 1D graph of tip displacement versus voltage, **Steps:**

I- On the Results toolbar, click on 1D Plot Group.

II- In the Label box, type Tip Displacement Vs Voltage.

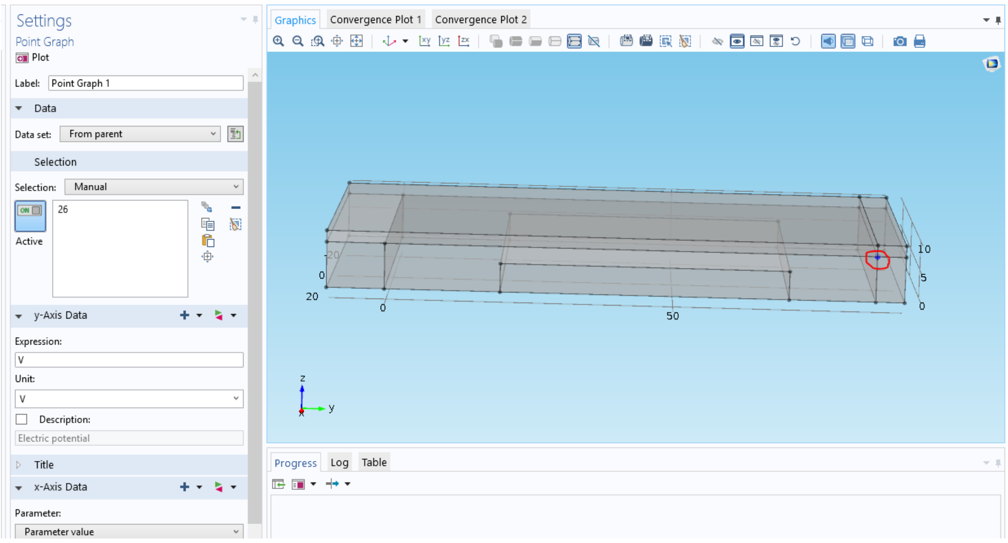
III- From the Tip Displacement Vs Voltage toolbar, click on Point Graph

IV- Select the tip of the cantilever as shown in figure below.

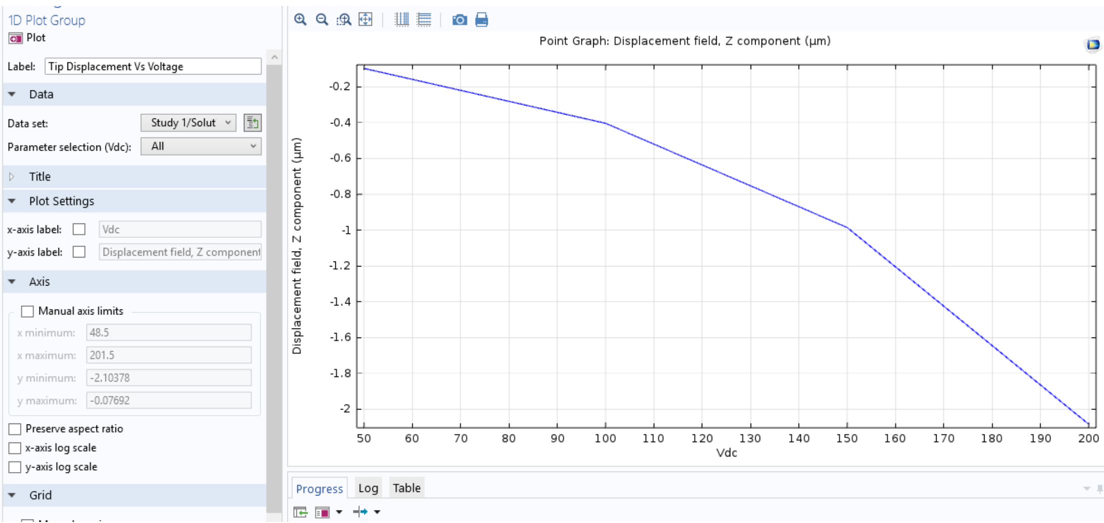
V- Press on Replace Expression on y-Axis Data

VI- Choose Model>Component 1>Electromechanics (Solid Mechanics)>Displacement> Displacement Field (Material)>w – Displacement field, Z component

VII- Click Plot



You should be able to see a figure similar to this



3- A 2D graph of capacitance (between the terminal 1 and ground faces-upper electrode face and lower cantilever face-) versus voltage, **Steps:**

I- On the Results toolbar, click on 1D Plot Group.

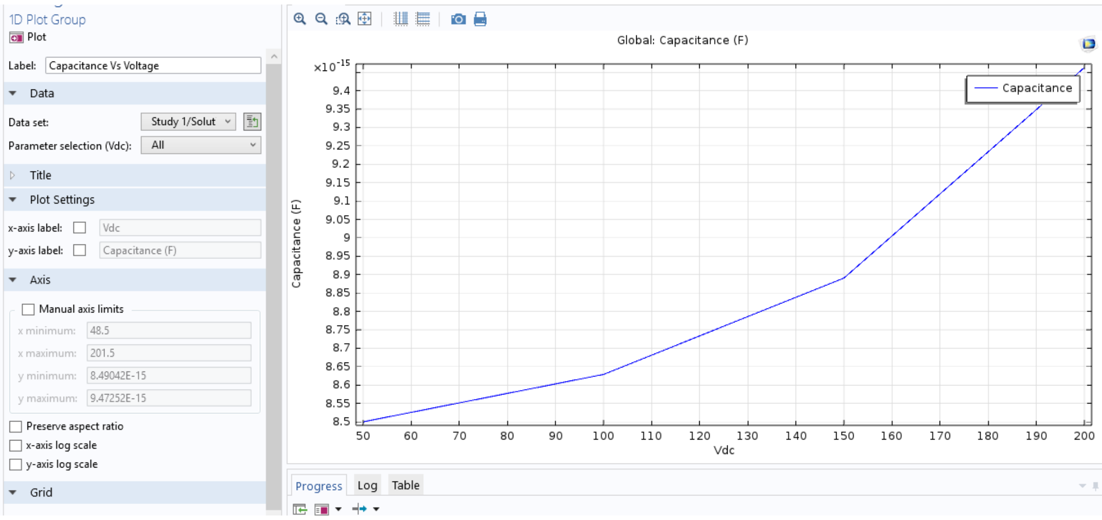
II- In the Label box, type Capacitance Vs Voltage.

III- From the Capacitance Vs Voltage toolbar, click on Global

IV- Choose Model>Component 1>Electromechanics> Terminals> emi.C11 - Capacitance

V- Click Plot

You should be able to see a figure similar to this



4- An animation of the structure displacement versus voltage, **Steps:**

I- From the Result toolbar, select Animation

II- From The Scene you will find a dropdown menu to choose results you need. By default it would be Displacement

III- Choose the Output Format you like and Browse where you want to save your animation, you can change frames per second to make the animation faster or slower

IV- The rest steps are clear and after you finish editing setting you can click Export to generate the Animation

COMSOL also enable you to automatically generate a document containing all your model selections (i.e. materials, physics) and results. To Generate the Report, just Right click on the Reports, choose Report Level (i.e. Brief) and edit the setting as you like, then click Write.

General Notes:

- You can use COMSOL to simulate the time response of the Switch to measure switch speed, through Time Dependent study.
- You can use COMSOL to simulate the RF performance of the switch through Electromagnetic Waves, Frequency Domain Physics and frequency domain study, of course you will need to make changes to the last example (i.e. you will need to add a substrate and RF ports and corresponding Physics boundaries…etc.). Results maybe in the form of S-parameters.
- You can use COMSOL to calculate Switch Natural Frequency through Solid Mechanics physics and Eigen Frequency Study.
- While the simulation is running you can notice two numbers on the right at the bottom of the window that shows physical and virtual memory usage
- While the simulation is running two plot are created (Convergence Plot 1 & 2), if the graphs start high then decrease with time (iteration number), then most probably the simulation will give results and you have built a working model. But if it keeps alternating (decreasing-increasing-decreasing), then most probably the simulation will keep trying to solve the equation but will exit after certain number of iterations.
- If you defined your physics right, and when your compute your study the simulation fails, then most probably that is a result of a poor meshing. Cases of poor meshing may be one of the following (but not limited to):
  1- It’s too coarse, so the equations can’t converge due to a relative high error. **Solution:** Try to make your mesh finer (don’t over mesh, just increase it step by step)
  2- It’s too fine, and your computer processing power and memory is not enough. **Solutions:**
     I- Make the mesh coarser if possible
     II- Try to reduce your model complexity and size (i.e. to reduce size, if your model is symmetric you can divide it to its half in your physics boundary selections. And you can remove any parts from the design

that is not very essential to your simulation, in other words do not contribute it simulations results or have very low contribution).

III- Use a computer with more processing power.

3- It is not the best shape to mesh with (triangular, swept mesh…etc.). **Solution:** Try to optimize you mesh selection to fit you problem

4- The Program reports an error like: inverted element at… or can't mesh certain faces or corners. **Solution:** use different mesh size or shape (note it doesn't always mean to just make the mesh finer, actually sometimes making it coarser solve this problem).

- COMSOL has built in documents, guides for each physics and models examples. It's always usefull to check them and practice on examples similar to what you are doing.
- When working on COMSOL you can always press F1 to get COMSOL built in help, and as you click on anything on COMSOL window the help automatically gives you information about that thing.
- COMSOL has some useful articles and videos (& Webinars) in its website.

Appendix B: UW-MEMS Layout Design Guidelines

This Appendix Show the UW-MEMS Layout Design Guidelines mentioned in UW-MEMS Handbook Version 5.0[30]

Introduction

These design guidelines and rules were determined during the process development stage and several microfabrication runs carried out at CIRFE cleanroom facility. The rules identify the physical and geometrical limitations of individual process steps. The herein presented guidelines are extremely important and must be considered at the design stage. If the guidelines are not followed closely by UW-MEMS users, the fabricated devices will not meet the specifications and will probably fail or malfunction.

In general, there are two types of rules. The first type of rules specifies the minimum feature sizes and minimum feature separation distances within a single layout layer, i.e. intra-layer design rules. The minimum feature size refers to the minimum side length of a trace that is feasible using UW-MEMS. In other words, if this rule is violated there is no guarantee that the feature will be produced on the wafer. Similarly, the minimum separation distance between adjacent features must comply with the design rules in order to be feasible. Failure to follow the minimum spacing design rule results in a merged feature.

The second type of design rules specifies the inter-level crossovers (overlaps) and separation distances. This is mainly imposed by the inevitable relative misalignment of the different layout layers throughout fabrication, and it will be shortly detailed. Both types of design rules are considered mandatory and should be followed closely by the designer.

General Outlines

The layout design rules for the UW-MEMS process are explained in the following tables and illustrated in schematic format following the tables. First, Table 1 outlines the different layer names, corresponding material thicknesses as well as layer numbers and description.

Table 1: Layer Names, Material Thicknesses, Layers Order, Layer Description and Comments

Layer Name	Material Thickness	Layer Order	Layer Description	Comments
"TiW"	50nm	1	Resistive Voltage Biasing	Resistive Layer
"D1" & "D1HOLE"	0.7μm	2 & 3	Dielectric	0.7μm SiO_2 to cover the bias lines
"G1"	1μm	4	Conductive Layer	40nm evaporated Cr + 70nm evaporated Au + 0.9μm electroplated Au
"D2"	0.7μm	5	Dielectric	50nm TiW + 0.7μm SiO_2
"A" & "D"	2.5μm	6 & 7	Sacrificial Layer	2.5μm Anchor and 1μm Dimple openings
"G2" & "G2R"	2μm	8 & 9	Conductive Layer	70nm sputtered Au + 1.9μm electroplated Au

Table 2 outlines the layers that are used during the microfabrication process. Please note that for the case of "Light Filed", you draw the features that you want to be remained on the wafer. For example, for TiW layer patterning, you draw the features or traces such as bias lines. For the "Dark Field", you draw the parts you want to be removed from the corresponding layer such as release holes or openings for anchors and dimples. Please pay special attention to this concept. Failure to do so will result in a reverse polarity devices.

In other words, for D1HOLE and G2R, you draw only the location of dielectric openings and release holes in gold, respectively. These layers will be subtracted from the D1 and G2 layers by CIRFE personnel prior to printing the second and seventh lithographic masks.

Table 2: Layer Names, Layer Polarity Type and Comments

Layer Names	Polarity	Comments
"TiW"	Light Field	Patterning TiW
"D1"	Light Field	Patterning **D1** without openings
"D1HOLE"	Dark Field	Additional layer for openings on the **D1** layer
"G1"	Light Field	Patterning G1
"D2"	Light Field	Patterning D2
"A"	Dark Field	Opening anchors between **G1** and **G2**
"D"	Dark Field	Dimples of **G2** for contacts of the switches as well as preventing the stiction of large plates
"G2"	Light Field	Patterning G2
"G2R"	Dark Field	Additional layer for release holes of the **G2** layer.

Table 3 presents the lithographic mask numbers with the respective GDSII indices of their constituting layout layers. GDSII is the only format that UW-MEMS accept from all users. Please use the GDSII numbers that are specified in the table for each layout layer to avoid confusion. Layers D1HOLE and G2R are just employed to create the openings in the D1 layer and the release holes in G2 layer, respectively. No lithographic masks are printed specifically for these layers. Please note that the dimples are meant for small features. Nominal surface area is 10μm by 10μm. However, they can be used for long lines, but it is recommended that the width of the lines be 10μm.

Table 3: UW-MEMS Masks and GDSII Layer Indices

Lithographic Mask	Layer Name(s)	GDSII Index
Mask #1	**TiW**	101
Mask #2	**D1 – D1HOLE**	102 - 110
Mask #3	**G1**	103
Mask #4	**D2**	104
Mask #5	**A**	105
Mask #6	**D**	106
Mask #7	**G2 – G2R**	107 - 109

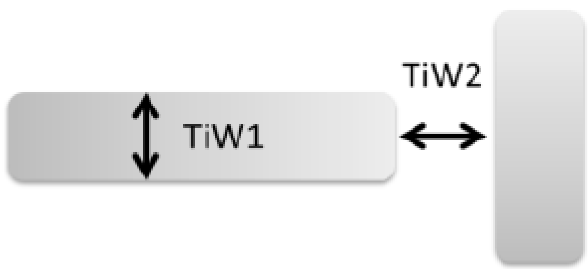
Overlaps & Enclosures

Generally, the following guidelines should be considered:

- For overlaps and enclosures of the layers, up to 10□m of misalignment between the layers is assumed. This is due to the limitations of our photolithography system. This is an advisory design rule.
- TiW lines are designated for the DC bias lines with no current flow. This layer is very thin, and it is not intended for power transfer.

The following outlines the specific layout design rules to which close attention must be paid. It is worth emphasizing that the minimum feature size and minimum spacing between features are limits to which the designers should strictly adhere. Ideally, adding a 10□m additional safety margin to these numbers may increase the yield of fabrication. Users can have round, orthogonal or any arbitrary shape in your layout. The release holes must be 10μm x 10μm squares with edge to edge distances not exceeding 20μm. Please do not use this layer to define geometries. The features are embedded to provide access to underneath the structural layer during the release purposes.

1. "TiW" resistive DC bias lines:



Description	Rule Label	Value (μm)
Width/Length of **TiW**	**TiW1**	≥ 10
Spacing of **TiW**	**TiW2**	≥ 10

2. First Dielectric "D1" stacked with "TiW" and Gold "G1":

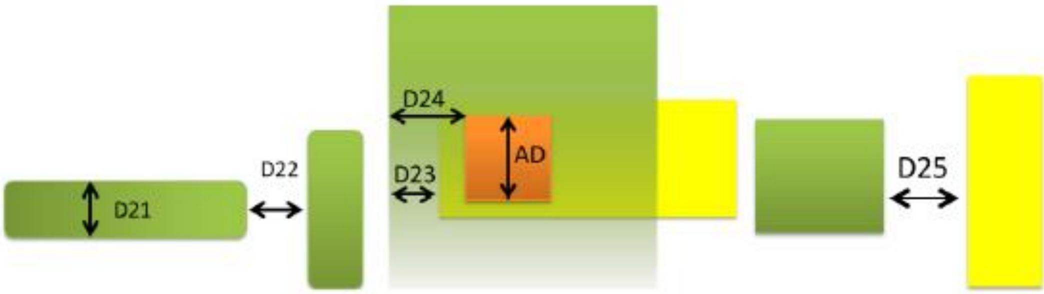
Description	Rule Label	Value (μm)
Extension of **TiW** from **D1**	**TiW3**	≥ 20
Width/Length of **D1**	**D11**	≥ 15
Spacing of **D1**	**D12**	≥ 15
Overlap of **D1** with **TiW**	**D13**	≥ 5
Extension of **D1HOLE** from **TiW**	**D14**	≥ 10
Width/Length of **D1HOLE**	**D15**	≥ 35
Overlap of **G1** pad with **TiW** or **D1**	**G13**	≥ 15
Overlap of **G1** pad with **TiW**	**G14**	≥ 10

Note: **TiW** lines MUST be always covered with **D1**, **G1**, or both.

3. First Gold "G1":

Description	Rule Label	Value (μm)
Width/Length of **G1**	**G11**	≥ 10
Spacing of **G1**	**G12**	≥ 10

4. Second Dielectric "D2" on top of TiW adhesion layer:

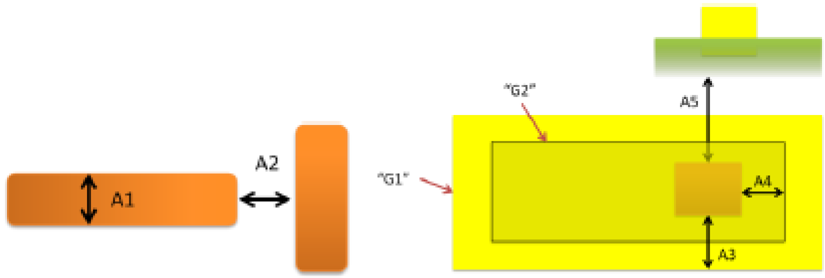


Description	Rule Label	Value (μm)
Width/Length of **D2**	**D21**	≥ 15
Spacing of **D2**	**D22**	≥ 15
Overlap of **D2** with **G1**	**D23**	≥ 10
Overlap of **D2** with **A**	**D24**	≥ 15
Spacing of **D2** from **G1**	**D25**	≥ 15
Feature size of **A** over **D2**	**AD**	≤ 200

Note: **D2** over 2 separated trances MUST be separated.

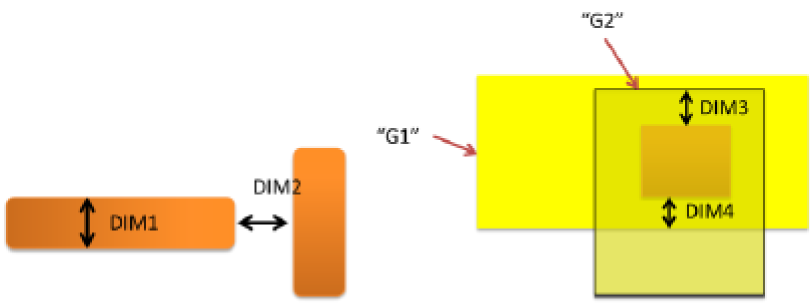
Note: Anchor on top of **D2** cannot be used as mechanical support but can be used for Metal-Insulator-Metal (MIM) capacitor.

5. Anchor "A" Openings:



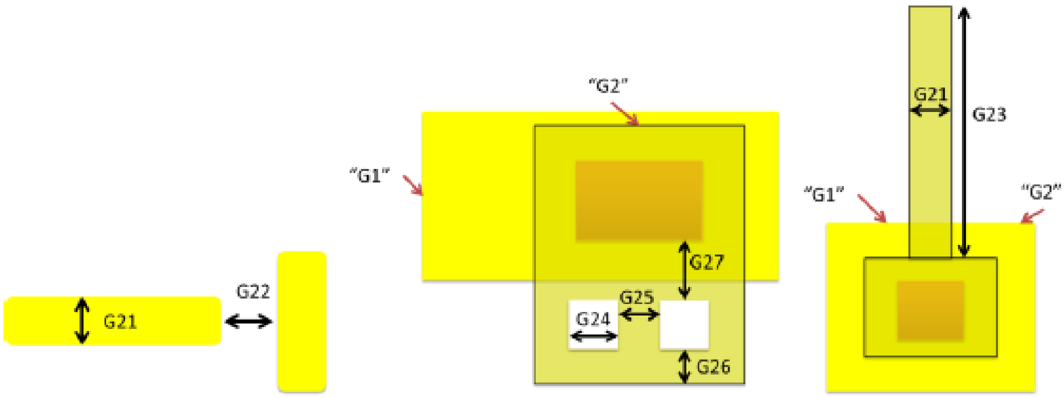
Description	Rule Label	Value (μm)
Width/Length of A	**A1**	≥ 10
Spacing of A	**A2**	≥ 10
Overlap of G1 with A (A MUST be covered with G1)	**A3**	≥10
Overlap of G2 with A (A MUST be covered with G2)	**A4**	≥ 5
Spacing of D2 from A	**A5**	≥ 10

6. Dimple "D" Openings:



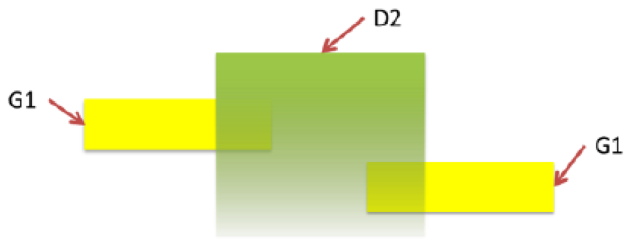
Description	Rule Label	Value (μm)
Width/Length of **D**	**DIM1**	≥ 10
Spacing of D	**DIM2**	≥ 10
Overlap of **G2** with **D**	**DIM3**	≥ 5
Overlap of **G1** with **D**	**DIM4**	≥ 5

7. Second Gold “G2”:



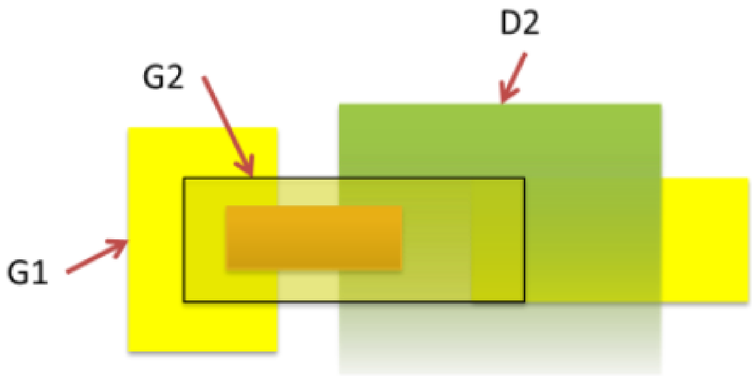
Description	Rule Label	Value (μm)
Width/Length of **G2**	**G21**	≥ 10
Spacing of **G2**	**G22**	≥ 10
Ratio of **G23/G21** when **G2** is not anchored to **G1**	**G23/G21**	≤ 30
Non-anchored length of **G2**	**G23**	≤ 1200
Width/Length of **G2R**	**G24**	≥ 10
Spacing of **G2R** (edge-to-edge)	**G25**	≥ 20
Spacing of **G2R** from **G2** edge	**G26**	≥ 10
Spacing of **G2R** from **A**	**G27**	≥ 10 & ≤ 30

8. Caution 1:



Note: This configuration results in short-circuit between the two G1 traces due to the conductive TiW thin layer underneath the D2 layer.

9. Caution 2:



Note: This configuration may result in short-circuit between the G1 and G2 traces through D2 layer.