IMPACT OF SURFACE ROUGHNESS ON THE PERFORMANCE OF RF MEMS CAPACITIVE SWITCHES

A Project Report

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PRAVEEN R

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THESIS CERTIFICATE

This is to certify that the thesis titled **IMPACT OF SURFACE ROUGHNESS ON PERFORMANCE OF RF MEMS CAPACITIVE SWITCHES**, submitted by **PRAVEEN R**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr.Deleep R Nair
Research Guide
Dept. of Electrical Engg.
IIT-Madras, 600 036

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ABSTRACT

KEYWORDS: Surface roughness, Resonant frequency, HFSS, Isolation loss, RF MEMS capacitive switch.

Main objective of this thesis is study the impact of surface roughness on the performance of RF MEMS capacitive switch for different surface roughness. Different surface roughness obtained here is by changing base area of hills and valleys of the surface in a microscopic level.

For this study, surface is created using positive and negative pyramids (hills and valleys) of rectangular pyramids. These pyramids are made with two base areas one with normal 1x1 and other is 2x2. Heights of these spikes are obtained from Gaussian distribution with mean and variation of 0nm and 1nm each. The maximum heights of spikes are limited to 3 x variation, that is 3nm and this includes for both positive and negative spikes. Placement of spike in the surface is random so each time the program is ran the result obtained would be a unique surface. Surfaces are generated for both dielectric and metal of the device. Distance between top and bottom surface (Metal and dielectric) are minimal which means that top most point of both surface will be in same plane.

Surface is taken as a matrix 12x12 with 1x1 pyramids placed in all cells. More than 40 surfaces are created and in each surface the pattern of these pyramids are varied. Pyramids with base area 2x2 are varied from 0% to 100% of total pyramids in the 12x12 surface and their isolation loss and resonant frequency is calculated. Surface with complete 2x2 pyramids and complete 1x1 gave isolation loss difference of about 0.12 dB and resonant frequency of 0.3 GHz. A mixture of these two pyramids gave resonant frequency between the above two surfaces and a higher isolation loss. For validating these results another simulation is done in COMSOL to get the capacitance of same surfaces and compared it with the capacitance value obtained in HFSS. Difference in capacitance for 100% and 0% in HFSS and COMSOL came as 0.06pf and 0.03pf respectively.

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Chapter 1

Introduction

1.1 Introduction to RF MEMS switch

RF MEMS switches were pioneered by IBM Research Laboratory in cooperation with Analog Devices [1] this was a milestone for the device to become what we see today. MEMS switches have become popular due to their better insertion loss and isolation loss. Though FET's are used in our day to day applications, RF MEMS switches get the upper hand when it comes to high frequency applications. This depreciation of FET is due to its poor insertion and isolation loss. Of all the advantages it offers over GaAs and Si FET's and its spectacular performance at high frequency, it suffers from relatively high cost of Hermetic packaging and reliability issues. There are wide range applications for RF MEMS switch like phase shifters, tunable filters, tunable antennas, satellites, defence applications and reconfigurable matching networks[2].

The device works with a mechanical movement of a beam to achieve short circuit and open circuit. This mechanical movement is done using the electrostatic attraction of plates or beams. In ON and OFF position the capacitance generated by beams determines how efficient the device will be. We will cover other parameters which effects switch performance.

1.1.1 Motivation

There are minor aspects that effect RF MEMS capacitive switch performance significantly yet goes unnoticed. Degradation of surface can lead to potential failure in core performance of switch because of this for sensitive applications of switch surface behaviour gets high priority during fabrication and taken care accordingly. Gaining more and in depth knowledge on what parameters of the surface effects the performance of switch always helps us in terms of high performance yield and reliability.

Major parameters that relate to surface are easy to understand like surface roughness, surface shape, surface distribution etc. Effect of varying surface roughness was studied and discussed in this MS thesis [3]. A new method for analysing the effect of surface roughness on the performance of the switch was proposed using the software HFSS and MATLAB [3]. In this study also same method has been used in fact this study is a continuation of that work. While in that work surface roughness and Gaussian variation of pyramids height are taken as a core matter, this study focus on more detailed and sensitive approach on how surface shape can have impact on the switch. His results indicate that the influence of surface roughness is not that effective in the up-state capacitance while it reduces the down-state capacitance of the switch. The latter effect causes the high frequency parameters, such as resonant frequency and isolation to change from the expected values which might lead the design to fall out of specifications. Taking this result as a reference we will see if this still stays valid for variations in the shape of surfaces.

1.2 RF MEMS switch

1.2.1 Equivalent circuit

Equivalent circuit of RF MEMS switch is a series RLC circuit. Most important parameter of MEMS switch is its capacitance, value of capacitance in the circuit changes when the state of the switch changes. In other words for down state and up state, capacitance values are different.

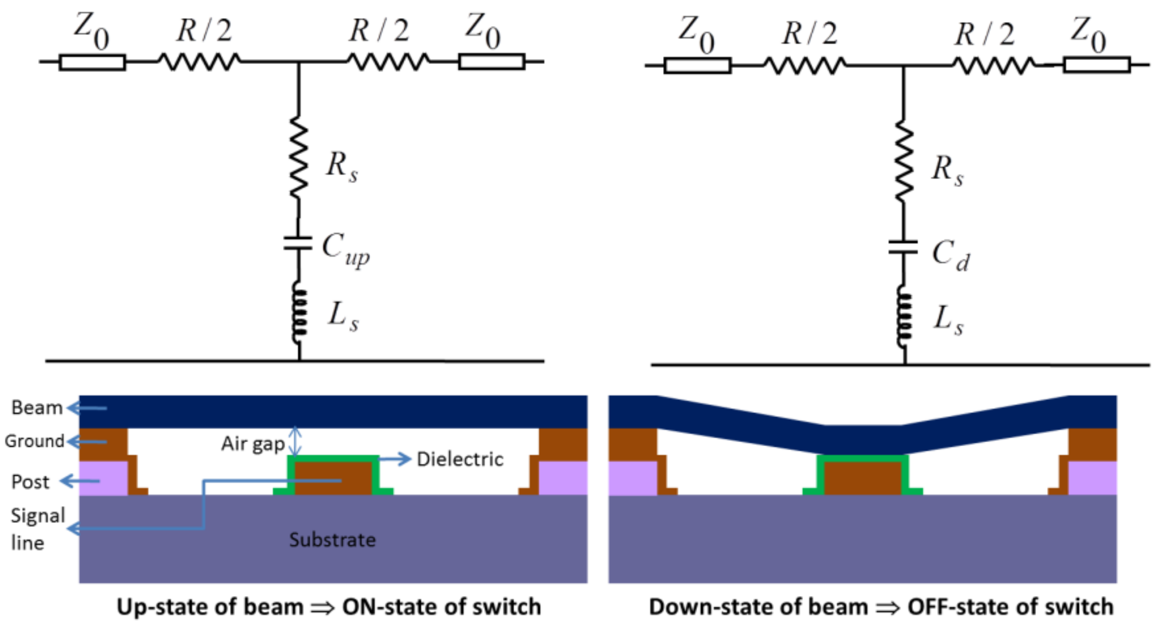

Figure 1.1: RLC equivalent circuit and cross section of the device at ON and OFF position respectively [3]

Impedance of the switch a up state and down state are given for figure 1.1

$$Z_{ON} = R_S + Z_{L_S} + Z_{C_{up}}$$

$$Z_{OFF} = R_S + Z_{L_S} + Z_{C_d}$$

Where

R_S Series resistance

Z_{Ls} Inductive reactance

Z_{Cd} Capacitive reactance

When the switch is in down-state the total impedance of the switch changes with the applied frequency. We can divide the impedance of the switch into higher frequency impedance, lower frequency impedance and resonant frequency impedance. By neglecting lower impedance at the above mentioned frequency ranges we can approximate Z_{OFF} as Z_{Ls}, Z_{Cd} and Rs respectively. As shown in figure 1.1 C_d and C_{up} are the down-state and up-state capacitance respectively. Inductance value remains same for both states as it mainly depends on the geometric aspects of the device and is independent of the state of the switch.

The contact resistance Z_0 between beam and ground comes in parallel with the beam resistance, R. Since dielectric is placed in middle of the beam, we can divide the beam resistance into two equal parts. This result in a T shaped circuit. Inductance in the device comes from substrate, signal line and other parts associated with it. R_s series resistance is the resistance of the path from signal line to beam its same in both states of switch as it is independent of the distance between beam and dielectric.

1.2.2 Up-state capacitance

Up-state capacitance can be defined as the capacitance between the beam and the signal line when the switch is in ON state. It mainly consists of two components of capacitance in series, capacitance due to air C_{air} and capacitance due to dielectric $C_{dielectric}$. C_{air} and $C_{dielectric}$ depends inversely on the distance between plates, as the beam goes higher g becomes much larger than t which results in C_{up} equal to C_{air}. Up-state capacitance gives an idea on how much of the signal is lost from input to ground when switch is in ON position generally we want it to be as small as possible. Equation for up-state capacitance is given below.

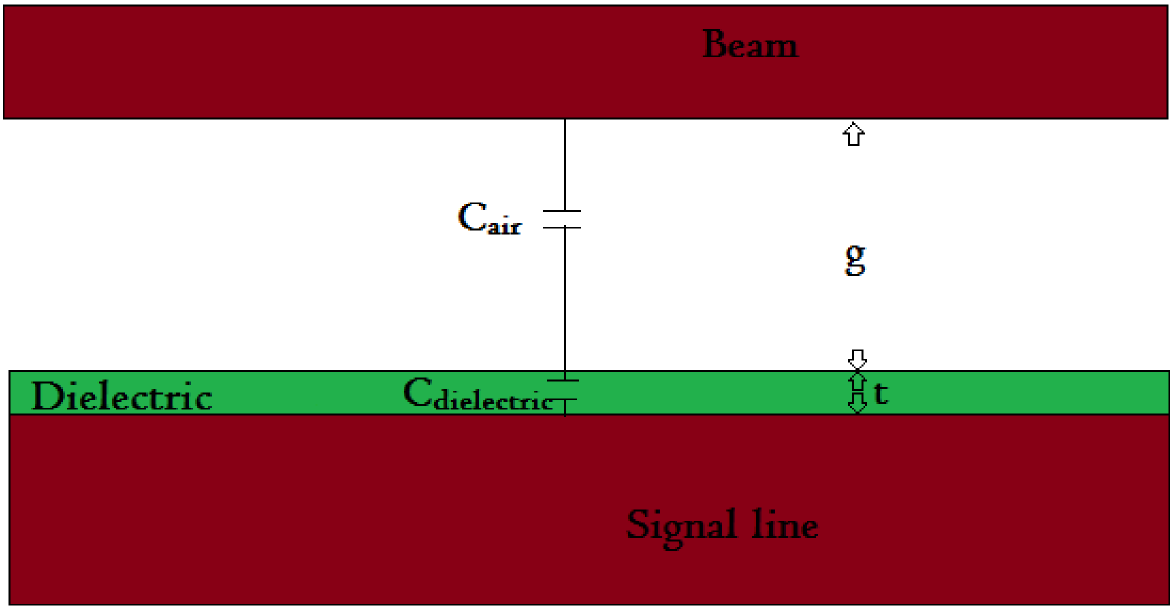

Figure 1.2: Pictorial representation of up-state of switch with C_{air} and $C_{dielectric}$, g is the distance between beam and dielectric and t is the thickness of dielectric layer.

$$C_{up} = \frac{C_{air}C_{dielectric}}{C_{air}+C_{dielectric}}$$

$$C_{air} = \frac{A\mathcal{E}_0}{g}$$

$$C_{dielectric} = \frac{A\mathcal{E}_0\mathcal{E}_r}{t}$$

g = thickness of sir below beam

t = thickness of dielectric

1.2.3 Down-state capacitance

It is the switch capacitance in the down-state position. In this thesis down-state capacitance has more importance since in all simulations we keep the switch in down-state or OFF state. At OFF state the beam and the dielectric are in contact, this will result in the elimination of air gap and the capacitance would be determined entirely by the dielectric thickness. We will see the effect on down-state capacitance as the surface roughness is varied in upcoming chapters. Down-state capacitance equation would be same as that of up-state with C_{air} removed.

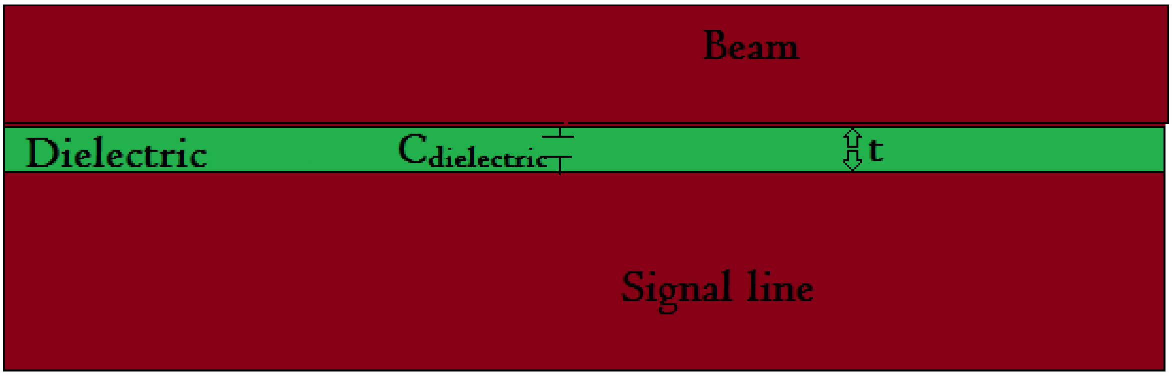

Figure 1.3: Pictorial representation of down-state of switch only $C_{dielectric}$ is present

$$C_{dielectric} = \frac{A\mathcal{E}_0\mathcal{E}_r}{t}$$

In the equation the area A is the overlapped region between signal line and dielectric.

1.2.4 Resonant frequency

In section 1.2.1 we saw the equivalent circuit of MEMS capacitive switch. We can define resonant frequency the frequency of the signal at which this circuit starts resonating. Resonance can occur for both up-state and down-state of the switch, but in this thesis resonant frequency is often used to refer frequency of down-state of the device.

Resonant frequency at down- state can be expressed as

$$f = \frac{1}{2\pi\sqrt{LC}}$$

L and C are inductance and capacitance at the down state of switch.

1.2.5 Insertion loss

Insertion loss is defined for the ON state of the switch; it is the ratio of output power to input power. At ON state, we expect the switch to be conducting normally and the input data to reach the output without any commotion. But the presence of up-state capacitance causes disturbance to the signal line, this will result in a small portion of the signal to flow to ground through beam. It can be expressed in equation as

$$Insertion\ loss\ in\ dB\ = 10\log\left(\frac{P_{out}}{P_{in}}\right) = 20\log|S_{21}|$$

P_{in} the power from the input port and P_{out} is the power delivered by the output port.

Ideally the insertion loss should be 0 dB ie $P_{out} = P_{in}$. Relationship between up-state capacitance and insertion loss can be expressed through S_{21} parameter. At the ON state of the switch,

$$S_{21} = \frac{1}{1 + j\omega C_{up} Z_0/2}$$

Z_0 is the port impedance.

1.2.6 Isolation

Isolation is defined as the ratio of output power and input power when the switch is in its OFF position or down state. This is an important parameter as it shows how well the down state of the device isolates the input and output. In this thesis we will be concentrating more on how the isolation is effected for different scenarios. In equation we can express isolation loss as

$$Isolation\ in\ dB\ = 10\log(P_{out}/P_{in})$$

P_{out}/P_{in} is obtained as S_{21} parameter in the simulation

As we can see Isolation and Insertion loss equations are same but their importance varies depending upon the switch state.

For better performance of the device isolation at resonant frequency should be as high as possible. This is determined by the impedance present in the path, also since capacitance and inductance of the device cancels out at resonant frequency we could analyse the defects or abnormalities incurred on the device from fabrication.

Isolation at resonant frequency is dependent on the series resistance and port impedance so it can be expressed as,

$$S_{21}|_{f0} = \frac{2R_S||Z_0}{2R_S||Z_0+Z_0} \cong \frac{2R_S}{Z_0}$$

1.2.7 Pull-in voltage

Pull-in voltage is the voltage that we apply between the beam and the pad below it, this result in the collapsing of the suspended beam. The value of voltage applied depends on the geometrical shape and the materials used. Voltage values could be around a few volts.

1.3 Summary

In this chapter we started with the equivalent circuit of RF MEMS capacitive switch and went through each of the components of the circuit. After that we discussed some topics which are important to know before we go further like insertion loss, down-state capacitance, up-state capacitance, resonant frequency and isolation. We will look into isolation loss, down-state capacitance and resonant frequency in more details in subsequent chapters.

Chapter 2

Components of the Switch

2.1 Introduction

In this chapter we will see how the switch works and main components used in the device.

RF MEMS switches are micro-machined systems that use mechanical means in the RF signal line to attain a short circuit or an open circuit. These switches are categorized by actuation method. There are two types of forces used for the actuation of RF MEMS switches; they are electromagnetic and electrostatic forces. The electrostatic force has a high actuation voltage, but has no current consumption. On the other hand, the electromagnetic force has a high current consumption and low actuation voltage. The electrostatic switches are most common switches and are of two kinds: series and shunt. The electromagnetic switches are used in the mm-wave and microwave regions. My work here is about electrostatic shunt switch.

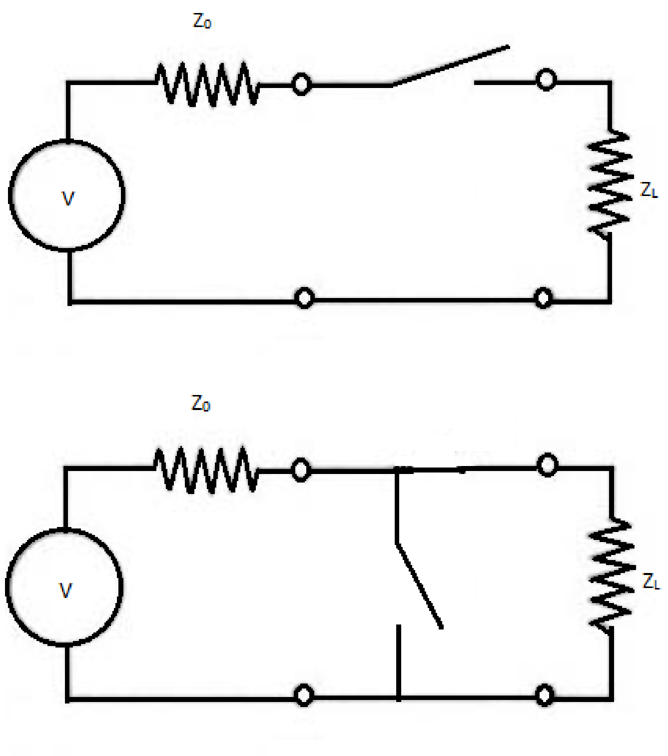

Figure 2.1: Series and Shunt switches

Ohmic and Capacitive coupling switches are examples of series and shunt switches. When the switch is actuated, Series switch is primarily disconnected and gets connected and when a required voltage is applied, the shunt switch is primarily connected and gets disconnected when an external voltage is introduced.

2.2. Switch design

As we discussed before all simulations in this thesis are done for voltage actuated electrostatic shunt switch. Main components of the switch is

1. Beam
2. Dielectric
3. Signal line
4. Ports
5. Substrate

2.2.1 Beam

Beam has the main role in the mechanical faction of the switch. When we want a short circuit in the switch that is OFF or down state we apply a voltage between the signal line and the beam which results in an electrostatic force between them. This force results in short circuit of the signal line and the beam. In simulation we consider the beam connected to ground and the signal line to a high dc supply voltage of 5V.

As we see in the equivalent circuit, resistance R which comes from beam can have high reliability issues on the switch, so we want the resistance to be as low as possible. Here we use material gold in beam for high conductance. In figure 2.2 we can see a top view of the beam used for simulation. Maroon coloured sheet is the signal line. Signal flows through the signal line, Magnitude of the signal flow is dependent upon whether beam is touching it or not. A large amount of stress can be observed on the beam because of the electrostatic force. This stress can lead to long term degradation or even failure of the switch. To take this into account during the simulation beam is designed with different smaller components rather than a single sheet of material; this will also help in mimicking the real beam during simulation.

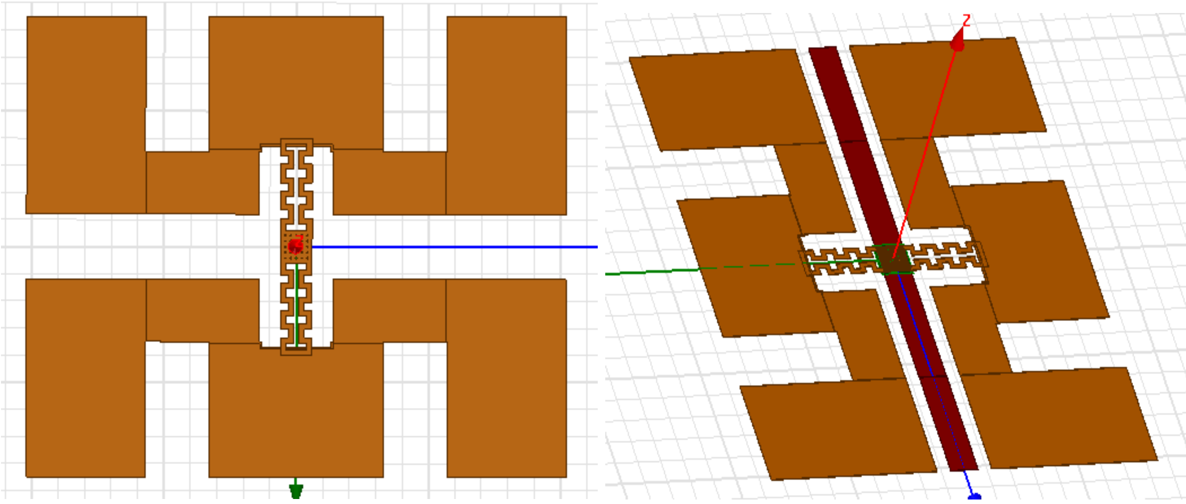

Figure 2.2: Top view of beam and beam with signal line

2.2.2 Dielectric

Dielectric used here is Silicon Nitride and it is placed between the beam and signal line, this will allow us to have a better control on the down state capacitance but this could also adversely affect the performance of the device through a phenomena known as dielectric charging. The 3D model of dielectric is a box shaped Silicon Nitride material which consists of 5 parts. 4 of them help the dielectric to hold its place. The 5th one is the biggest and main part of the dielectric; it is located in the middle and different surfaces are put on top of it. For all simulation thickness of the dielectric is fixed as 100 nm.

Figure 2.3 shows the dielectric model used in the simulation as we can see majority of the middle part is covered with rectangular pyramids which make up most of the surface roughness. The entire structure is in an arc shape which allows signal line to pass under it.

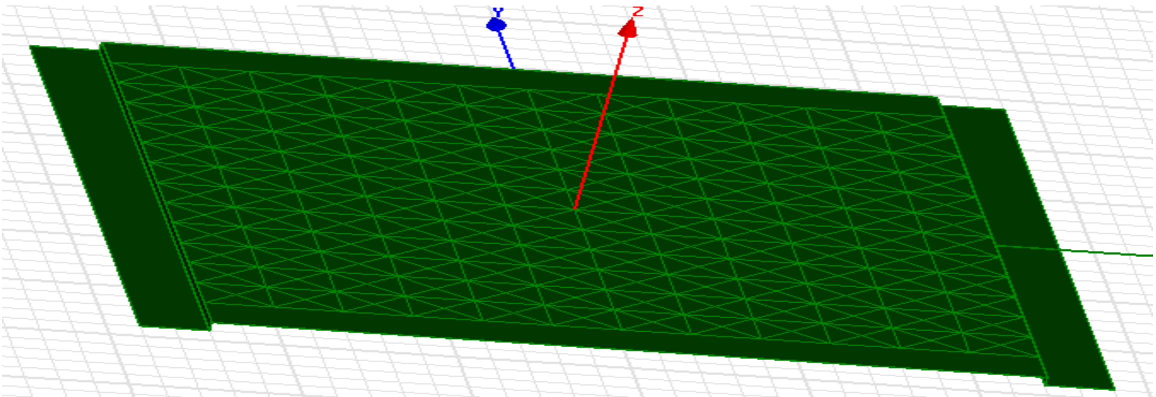

Figure 2.3: Dielectric in the switch here 1x1 pattern is imprinted on dielectric

2.2.3 Signal line

As we see in figure 2.2 signal line (Figure 2.4) is defined as the path at which high frequency signal is propagated. We decide if the switch is ON or OFF depending upon the relative position of beam and signal line. For better conductivity signal line is made of gold and it passes under a Silicon Nitride dielectric. Ports are kept at both extreme sides the signal line where the inputs and outputs are defined.

Isolation loss and insertion loss of the switch is measured from the power of signal coming through the signal line. Signal line plays a major role in determining the inductance in the equivalent circuit.

Signal line has a 2 µm thickness and 2040 µm length.

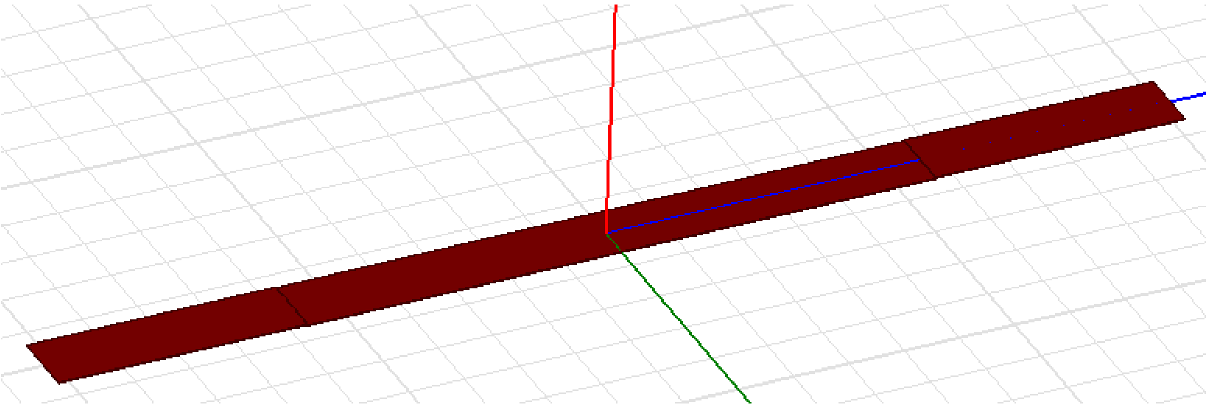

Figure 2.4: Signal line used in the switch

2.2.4 Ports

Ports are used to generate and receive signals. MEMS switch is a two port device with an input port and an output port. Return loss is another important parameter of the device. It gives us an idea of the mismatch of characteristic impedance between the switch and transmission line or signal line. P_{ref} here referred as the power returned from the switch to input port. Isolation loss in the simulation is measured as the S_{21} parameter P_{ref} should come as S_{11} parameter but we will not be going in details about return loss.

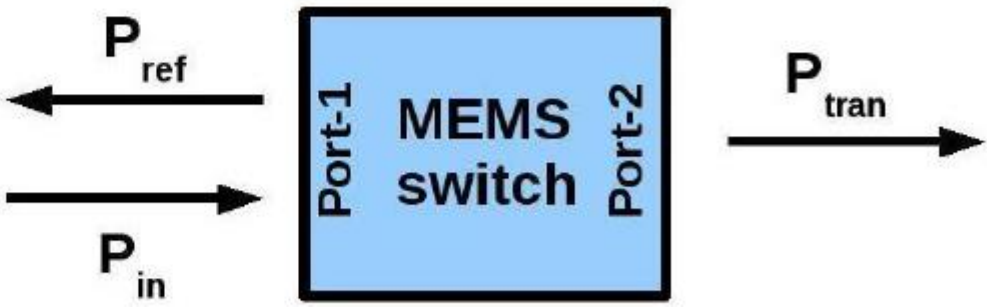

Figure 2.5: Equivalent port block diagram of switch [8]

2.2.5 Substrate

Substrate gives the device a basic platform to stand on also it should be an insulator to prevent any unnecessary short circuits, further for better isolation an oxide layer is also sandwiched between CPW lines and substrate. Considering the above conditions the material used is glass and has a dimension of 500 µm height 2040 µm length and 2000 µm width as shown in figure 2.6.

Though the substrate gives the device a stable platform and protection from any outside substance it also significantly contributes to inductance of the switch. This must be appropriately optimized to get a proper resonant frequency for the corresponding applications.

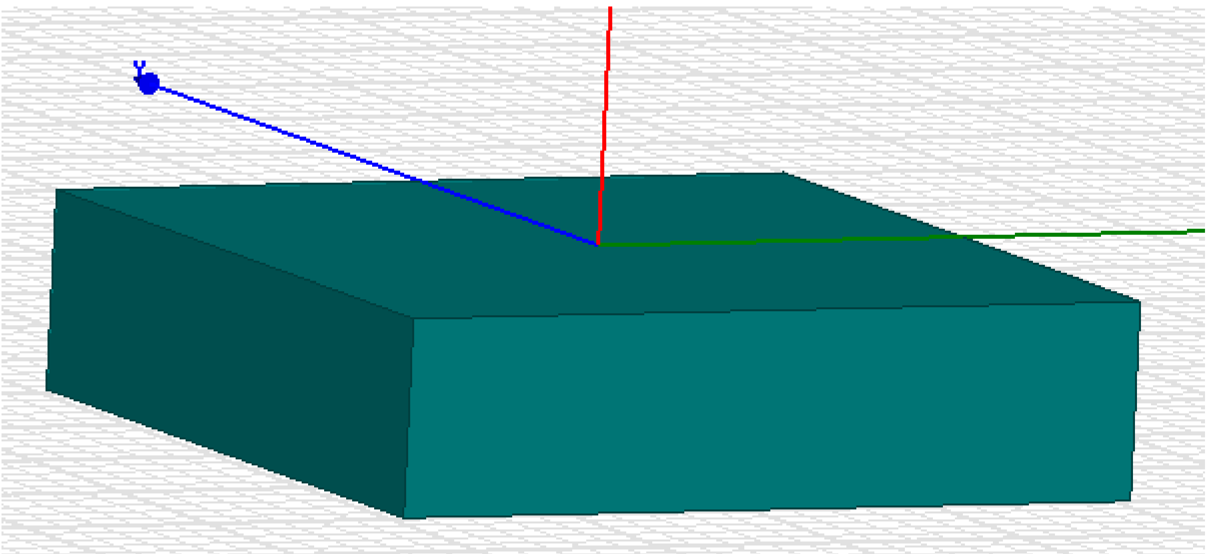

Figure 2.6: Substrate block used in switch

2.3 RF MEMS switch working

As we discussed before the main working concept of the switch is the mechanical faction and we will cover it in this section.

The switch mainly consists of following parts three CPW lines, one bridge over the middle CPW, substrate to hold all the component, dielectric to improve capacitance and one DC supply voltage to trip the bridge to different states. The DC supply voltage is applied such a way that the bridge has ground voltage and the signal line has high voltage. This will result in building up of static charges in the planes consequently an electrostatic force comes into picture. If this force is more than a threshold value then the bridge collapses to signal line. Now the signal line is shorted with beam the signal starts flowing to ground through the bridge this state is called down state or OFF state. In figure 2.7 we can see the switch in OFF state the red colour is the bridge which bend down to the signal line due to electrostatic force. If we remove the DC supply voltage then the beam comes back to its normal position which is ON or up state.

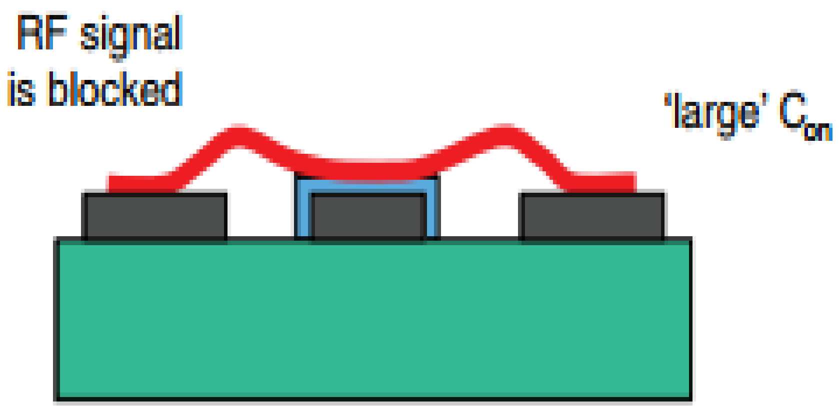

Figure 2.7: Downstate of the RF MEMS switch [9]

All of my work is when switch is in its down state. In down state actually bridge and signal line does not make contact directly instead there is a layer of dielectric in between them and the bridge comes in contact with the dielectric. This dielectric thickness can be varied to change the capacitance thereby can change the resonant frequency also. Dielectric has high impact on the performance of switch. In OFF position we are more concerned about isolation, that is we want to minimize the amount of signal going to output port when most of the signals are going to ground through bridge. As far as this project is concerned isolation depends upon the capacitance between the bridge and dielectric. We will see in later section that surface roughness on dielectric can have impact on resonant frequency and isolation loss.

If we consider ON state of the device the beam will be hanging on top with no physical contact with the signal line or dielectric this results in open circuit. But since the distance between them is still in nano range there could be considerable capacitance, this capacitance can result in high insertion loss. Presence of capacitance there will allow short circuit current for some particular frequency which results in loss of signal so we want insertion loss as minimal as possible.

2.4 Summary

In this chapter we went through all main parts of the switch in detail and saw their importance in this simulation also we went through the working mechanism of the switch.

Chapter 3

Methodology

3.1 Introduction

Here we will discuss how simulation is done and what all methodologies were taken to achieve the results.

3.2 Software used

3.2.1 HFSS (High Frequency Structural Simulator)

Main software used for the simulation is HFSS. RF MEMS switch modelling is done in HFSS. For all simulation device was in OFF or downstate position. HFSS is a commercial finite element method solver for electromagnetic structures from ANSYS. The acronym originally stood for high frequency structural simulator. ANSYS HFSS software is the industry standard for simulating high-frequency electromagnetic fields.

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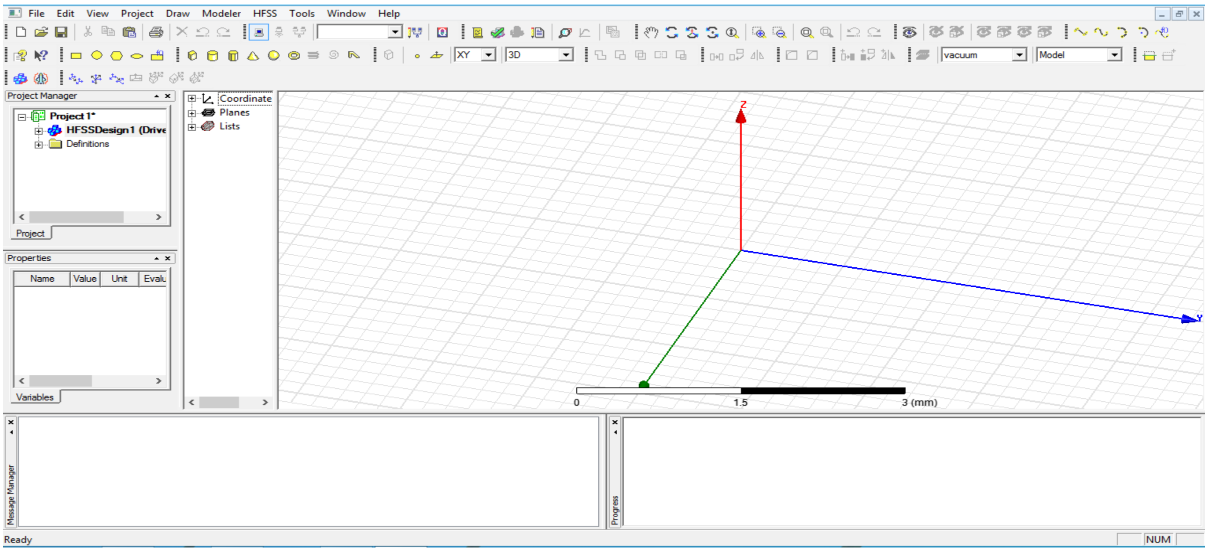

Figure 3.1: HFSS user interface

3.2.2 MATLAB

This is one of the most common software used by all engineer for all mathematical calculations. For this project I used it for generating random number in Gaussian distribution and to create random 2-D surface matrices which is later put in HFSS to generate a 3-D surface model.

As I mentioned before MATLAB is used to generate surface patterns which is later transferred to HFSS through a visual basic code. HFSS supports running .vbs file as scripts. Height of pyramids, amount of pyramids and their nature are determined from MATLAB program. How this is done we shall discuss in later part but for now we can say that to start a simulation we need to run some programs on MATLAB and get pattern and random distribution for height.

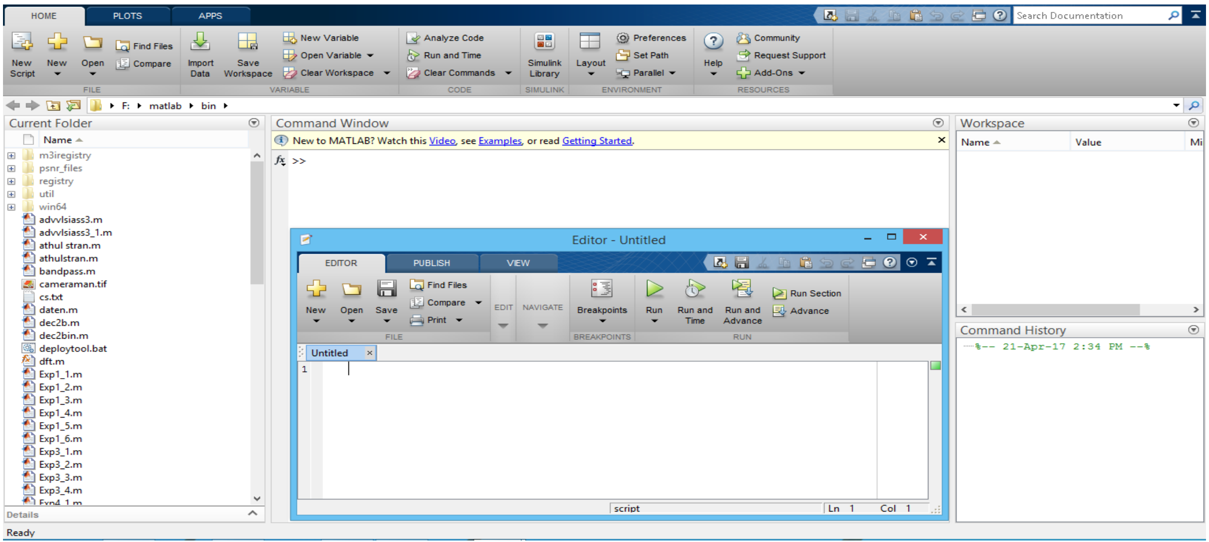

Figure 3.2: MATLAB user interface

3.2.3 COMSOL

COMSOL is software we use for modeling and research purpose. In this project we use COMSOL for confirming or obtaining more credibility for the result that we got from HFSS simulation. Capacitance of RF MEMS switch in its down state is found through COMSOL this is then compared with HFSS result. Importance of COMSOL in this project is comparatively less as it is used only for the sake of reliability of results. Getting almost same result from COMSOL is not the best way to get the confirmation on our result still it increases the chances of these results being correct.

3.3 Process Flow

We will see how the results are obtained step by step.

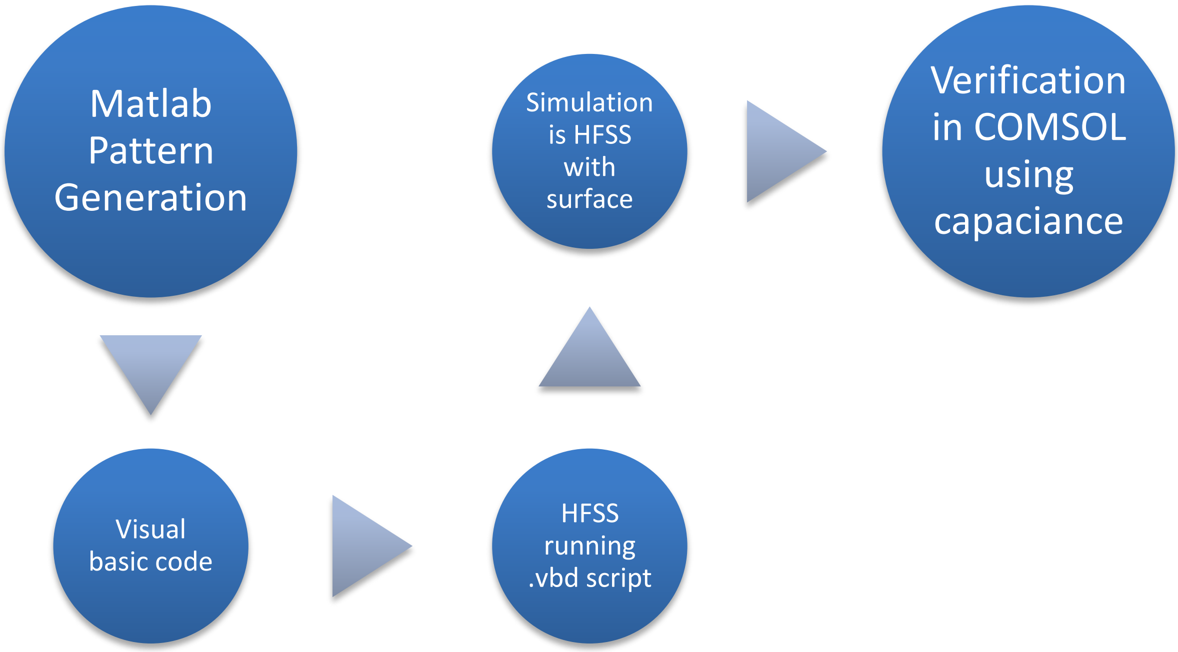

Figure 3.3: Simulation process step by step

3.3.1 MATLAB pattern generation

For all the simulation the surface size is limited by 12x12 matrix. So in MATLAB for the pattern generation a 14x14 matrix is taken which we will see why shortly. Before we go any further we have to define two types of pyramid, one with base area of 1x1 cells (1x1 matrix) and other with 2x2 cells (2x2 matrix).

Output and input of the program is a 14x14 matrix and an area wise percentage number of 2x2 pyramids respectively. In the matrix given in figure 3.4 the percentage value is 10%, which means area occupied by the 2x2 pyramids is 10% of total area, note that the matrix directly generated will have values 111 and 1 for 2x2 and 1x1 respectively. In later stage the matrix will be manually edited so that values 1 and 0 will be replaced by 40, this is done because the vbs is configured or programmed to accept matrix in that way, keep in mind that the numbers 40, 1, 0 and 111 does not hold any significance.

Now we shall see how the program generates the surface pattern. Initially the program randomly selects a cell (reference cell) which it intends to convert to 2x2 pyramid. It assigns number 111 to three neighboring cells and the reference cell; those three neighboring cells are selected in such a way that the reference cell comes in the bottom right corner of the 2x2 cell cluster. So these 4 cells represent one 2x2 pyramid in the surface. This method is repeated until the matrix satisfies the input percentage value.

For the next iteration program selects another random cell in the matrix, one thing to take into account here is that any cell that is in the neighborhood of the 2x2 pyramid cannot be selected as a reference cell to assign 111 since it will overlap (clearly right and bottom side of the cell) with the previously created matrix, these cells are assigned a different number 0 so that the program will not select these set of cells for making a 2x2 pyramid in future iterations. Assignment of 0 will be done when corresponding 2x2 pyramid is created. As we can see in the figure 3.4 2x2 pyramids are created with value 111 and cells with values 1 are 1x1 pyramids. All cells with value 0 will be assigned the number 1 i.e. 1x1 pyramid after program is done with the generation of 2x2 pyramids.

1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	111	111	0	1	1	1	1	1	1	1	1	1	1
1	111	111	0	1	1	1	1	1	1	1	1	1	1
1	0	0	0	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	111	111	0	1	1	1	1	1	1
1	1	1	1	1	111	111	111	111	0	1	1	1	1
1	1	1	1	1	0	0	111	111	0	1	1	1	1
1	1	1	111	111	0	1	0	0	0	1	1	1	1
1	1	1	111	111	0	1	1	1	1	1	1	1	1
1	1	1	0	0	0	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 3.4: Basic 14x14 matrixes generated by MATLAB

We are using 14x14 because we are assigning 2x2 cell in a diagonal fashion (bottom right) from cell address (14, 14) to (1, 1), if we keep reference cell at 14x14 the program will give an error since it won't be able to find any cell to assign 0. So for prevent any error or miss happening from program side 2 more rows and columns are added. While importing this matrix we shall select only 12x12 matrix and delete other unnecessary cells. At the end of the program all cells with value 0 and 1 are reassigned with a value 40 which now represents a 1x1 cell.

Figure 3.4 has 10% 2x2 cells on 12x12 matirx. For this project we have considered 4 possibilities 0%, 25%, 66% and 100%. Where 0% is a surface with all 1x1 cells and 100% is a surface with all 2x2 cells. 25% and 66% are shown in the figure with a graph representing both types of cell using different colors. 0% and 100% will have all the cells covered by 1 (1x1 pyramids) and 111 (2x2 pyramids) respectively. Reason why we took 66% is that this algorithm has a limit when it comes to putting maximum number of 2x2 cells in the matrix since there will be a lot of space that remains between these cells that cannot accommodate any other pyramids but 1x1.

	1	2	3	4	5	6	7	8	9	10	11	12
1	40	40	40	40	40	40	111	111	40	40	40	40
2	40	40	40	40	40	40	111	111	40	40	40	40
3	111	111	40	40	111	111	40	40	40	40	40	40
4	111	111	111	111	111	111	40	111	111	40	40	40
5	40	40	111	111	40	40	40	111	111	40	40	40
6	40	40	40	40	40	40	40	40	111	111	40	40
7	40	40	40	40	40	111	111	40	111	111	40	40
8	40	40	40	40	40	111	111	40	40	40	40	40
9	40	40	40	40	40	40	40	111	111	40	40	40
10	40	40	40	40	40	40	40	111	111	40	40	40
11	40	40	40	40	40	40	40	40	40	111	111	40
12	40	40	40	40	40	40	40	40	40	111	111	40

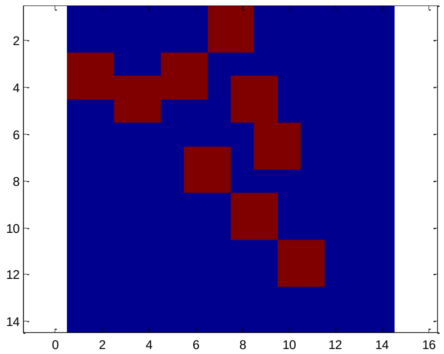

Figure 3.5: This is the final 12x12 matrix used for surface generation this is for 25%. Colour graph is shown for better understanding.

	1	2	3	4	5	6	7	8	9	10	11	12
1	40	40	111	111	40	40	111	111	40	40	40	40
2	40	40	111	111	40	40	111	111	111	111	40	40
3	40	111	111	111	111	111	111	40	111	111	40	40
4	40	111	111	111	111	111	111	40	111	111	111	111
5	111	111	40	40	111	111	111	111	111	111	111	111
6	111	111	111	111	111	111	111	111	40	40	111	111
7	40	40	111	111	40	40	40	40	111	111	111	111
8	40	111	111	111	111	111	111	40	111	111	40	40
9	40	111	111	111	111	111	111	40	111	111	111	111
10	111	111	40	40	111	111	111	111	111	111	111	111
11	111	111	111	111	111	111	111	111	40	111	111	40
12	40	40	111	111	40	40	40	40	40	111	111	40

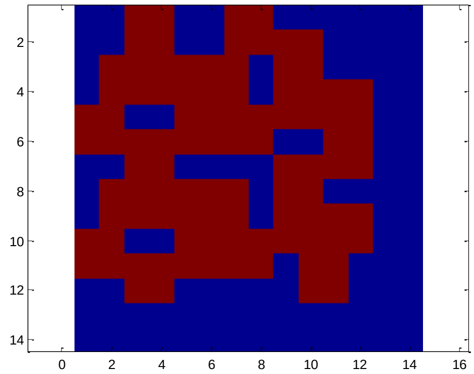

Figure 3.6: This is the final 12x12 matrix used for surface generation this is for 66%. Colour graph is shown for better understanding.

MATLAB program for this could be written with the help of a few for loops and careful matrix assignment operations.

Other than pattern generation MATLAB came in handy for generating the height of these pyramids. These heights are obtained from Gaussian distribution with mean of 0 nm and variance 1 nm. Mean is taken 0nm assuming that pyramids and inverted pyramids are equally distributed and variance of 1nm is taken so that it could be compared with the previous work [3]. Maximum height of the pyramids is restricted to 3nm upward and downward. The following code generates the random heights required and values which are less than 0.5nm are removed manually since they cross the lower threshold of the minimum distance resolution of HFSS.

```
s=1;
m=0;
y = s*randn(72,1) + m;
```

Where s is the variance, m is the mean and y is the height.

The value inside randn function is the total number of cells present in the matrix, while counting the cells 2x2 pyramid with four cells must be considered as 1 and accordingly all heights are generated. All these values of surface pattern and heights are copied to an excel file which is used by a visual basic code to generate the surface through HFSS.

3.3.2 Simulation in HFSS

Since HFSS supports running .vbs scripts creation of surface is quite simple. As we can see in the figure 3.7 when we start running the script in a few minutes the surface is created, it would have been a difficult task otherwise.

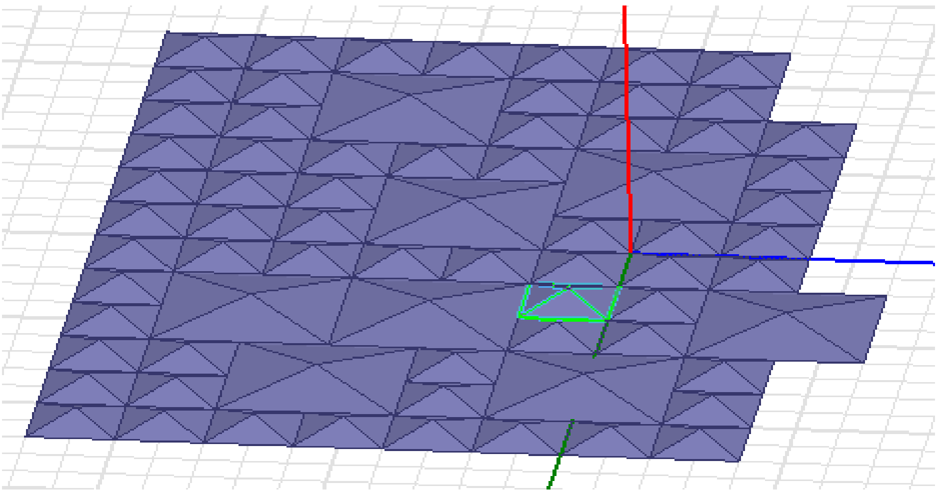

Figure 3.7: Surface creation while vbs script is ran on HFSS

If we look closely figure 3.7 consists of only pyramids and has only thickness in positive z direction. So to create inverted pyramids a box of 3 nm height and of same dimension as the surface is created and put below the surface (note that this surface has inverted pyramids). Then the surface is subtracted with the newly created box to get cavities. When we do the subtract operation we will loss pyramids of the surface. To prevent this we will put a copy of the surface on top of this and split it with respect to x axis so that pyramids are left behind and inverted pyramids are eliminated. These two partitions are united in the end to get the surface for simulation. This particular process of surface creation is done only for dielectric surface, for beam surface we will do the same except that the box will be put on the top of the surface since the surface of the beam will be upside down compared to dielectric.

Another thing to take care is the distance between these surfaces, for all simulations the plane which has the peak of maximum height of both surfaces are aligned. This is an approximation to represent touching of beam and dielectric. In reality at down-state of the device both surface will hit each other. They even go beyond this point and will cause damage to surface and make it different each time it hits.

Simulation is carried out after imprinting these surfaces at their places in the switch and for each simulation height if the dielectric is fixed at 100nm. Extraction of S_{21} parameter is done and isolation loss of the device was observed. Simulations are done with beam surface fixed at 100 % and varying the dielectric surface. One simulation is done for 0% and 100% as their surface pattern does not matter and around ten simulations are done for 25% and 66% each.

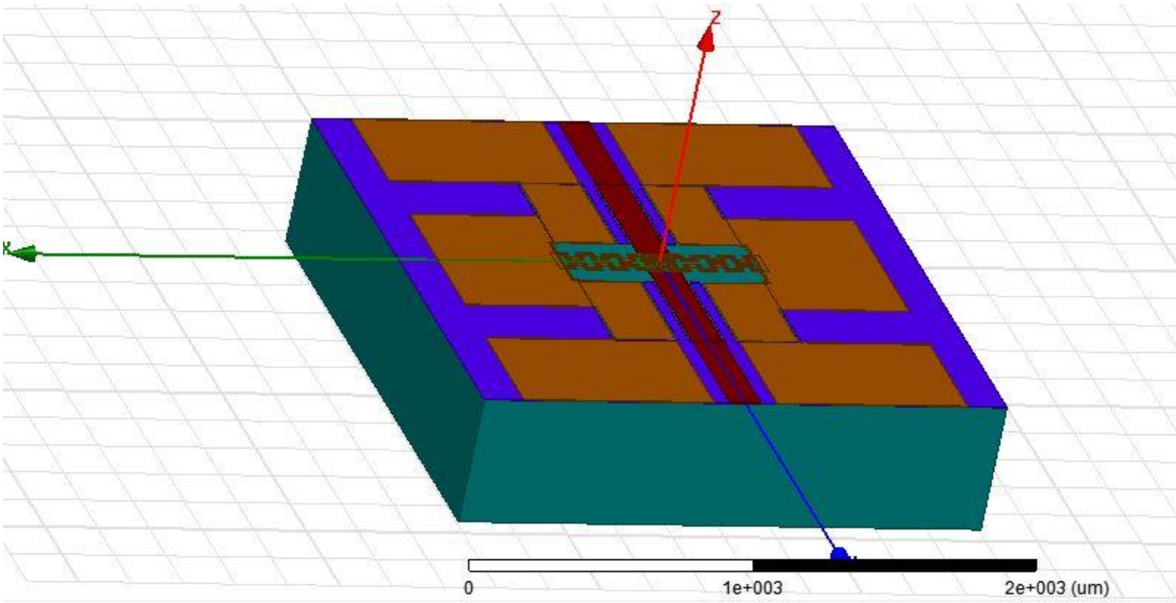

Figure 3.8: Completed model of RF MEMS capacitive switch

Other than isolation loss and resonant frequency capacitance was also extracted for all surfaces in order to compare it with COMSOL capacitance results. The scattering parameter, S_{21}, obtained using the simulations performed in HFSS is used for extracting C_d based on the following equation [6].

$$S_{21} = \frac{1}{1 + jwC_d \frac{Z_0}{2}}$$

For $wC_d Z_0 >> 2$ which corresponds to $|S_{21}| << 10dB$

$$|S_{21}|^2 = \frac{4}{w^2 {C_d}^2 {Z_0}^2}$$

The switch is capacitive in nature for the frequencies much less than the LC resonant frequency. C_d is extracted from this region of frequencies where $|S_{21}| << 10dB$

3.3.3 Simulation in COMSOL

As we discussed earlier this simulation is done just to give reliability to the results obtained in HFSS. The surfaces required for the simulation is extracted from HFSS in a format which can later be imported to COMSOL.

Two surfaces beam and dielectric are imported to COMSOL and dimensions are given in such a way that it matches with model in HFSS. Distance between these surfaces is kept minimal and air is introduced in the gap between them. A voltage of 5 V is applied at the dielectric plate and the beam is grounded. With appropriate meshing and calculation the capacitance was obtained for 0%, 100%, 25% and 66%. Most important capacitance value of all was that of 0% and 100% note that in these entire simulations beam is kept 100% 2x2 and dielectric surface is varied from 0% to 100%. We shall see the results obtained in HFSS and COMSOL in upcoming chapter.

In COMSOL electrostatic physics is used and materials Si_3N_4, Air and gold was used for dielectric gap and beam respectively.

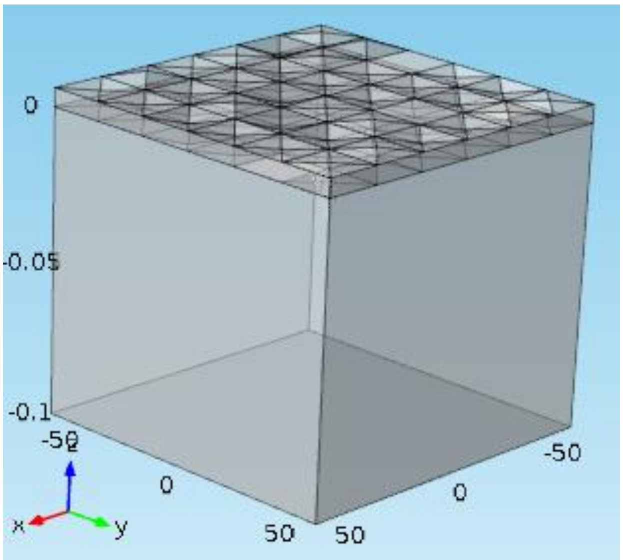

Figure 3.9: COMSOL model for extracting capacitance top is beam and bottom is dielectric

3.4 Summary

We went through introduction to all software used and their importance in this project in detail. We saw the flow chart about the process required to complete this project. Also we saw how each step is done, from surface pattern creation in MATALB to capacitance simulation in COMSOL. Out of all software we used HFSS was the core software for this project but without MATLAB program it would be impossible for HFSS to create a surface as required.

The capacitance equation used in HFSS is valid only for S_{21} less the 10dB. In COMSOL the capacitance extraction is based on the normal standard parallel plate capacitance equation. Surface in COMSOL is imported from HFSS and arranged in such a way that it resembles the beam dielectric interface.

Chapter 4

Results and Conclusion

4.1 Introduction

In this chapter we shall go through the results obtained for different surface configurations in detail. We shall also see future works related to this project in the end. Before we go any further refreshing the basics we have covered so far would be helpful. For simulations we have considered 4 surface configurations 0%, 100% 25% and 66%. We are considering 66% instead of conventional 50% or 75% is because MATLAB program cannot generate a higher percentage surface than 66%. These patterns are given to HFSS in order to generate surfaces required for final simulation, in figure 4.1 we can see respective surfaces created.

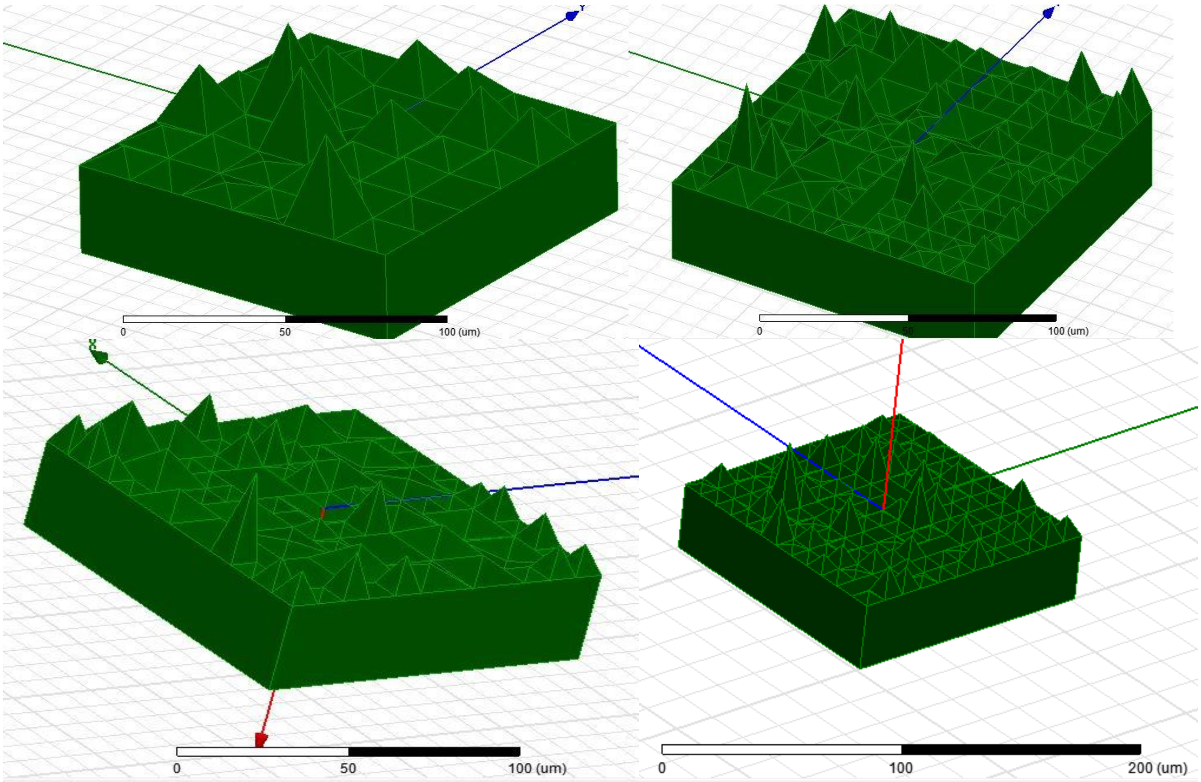

Figure 4.1: Some of the surfaces created in HFSS from top left clockwise 100%, 25%, 66% and 0%

4.2 Results and Conclusion

Around more than 40 simulations are done with different surface patterns and heights and their isolation loss and resonant frequency was calculated. Two types of simulation is considered, first one with the beam surface fixed at 100% 2x2 and varying the dielectric surface and second one is by keeping the dielectric surface fixed at 100% 2x2 and varying the beam surface. Second type did not have much noticeable effect as the first type on isolation loss and resonant frequency. As we have seen before, surface roughness is defined as the variance of the Gaussian distribution associated with the heights of the pyramids. For this project two variances or surface roughness is considered and they are 1 nm and 5 nm. Doing simulation with these values will help us compare the result with previous work [3].

Simulation is done with surface roughness fixed at 1nm and is tabulated in 4.1, 4.2 and 4.3.

Percentage	**Resonant Frequency (GHz)**	**Isolation loss (dB)**
25_1	10.5	-55.30279372
25_2	10.5	-54.73997971
25_3	10.5	-55.38555229
25_4	10.6	-55.21474015
25_5	10.5	-55.12738204
25_6	10.6	-54.99668766
25_7	10.6	-55.3877501
25_8	10.3	-56.13807711
25_9	10.5	-55.56584596
25_10	10.5	-54.85943471
Average	10.51	-55.27182435

Table 4.1: Values of Resonant frequency and isolation loss for different surface patterns with 25% 2x2. Beam surface fixed and dielectric surface varying

Percentage	Resonant Frequency (GHz)	Isolation loss (dB)
66_1	10.6	-54.84807826
66_2	10.5	-55.48204948
66_3	10.5	-55.35819034
66_4	10.5	-55.67491495
66_5	10.5	-55.594397
66_6	10.6	-55.23115126
66_7	10.7	-55.73258972
66_8	10.6	-54.92648187
66_9	10.6	-55.50115396
66_10	10.6	-54.7107653
Average	10.57	-55.30597721

Table 4.2: Values of Resonant frequency and isolation loss for different surface patterns with 66% 2x2. Beam surface fixed and dielectric surface varying

Percentage	Resonant Frequency (GHz)	Isolation loss (dB)
0%	10.4	-54.60674738
100%	10.7	-54.72476651

Table 4.3: Values of Resonant frequency and isolation loss for different surface patterns with 0% and 100% 2x2. Beam surface fixed and dielectric surface varying

As we can see in table 4.1 and 4.2 for each percentage of 2x2 surface 10 different patterns of surface were taken, later we will find the median value of these for better understanding. Their resonant frequency and isolation loss variations are minor for different pattern in 25% and 66%. But when it comes to percentage variation from 0% to 100% we can see significant changes in the resonant frequency and the isolation loss.

%	Resonant Frequency (GHz)	Isolation loss (dB)
0	10.4	54.6067
25	10.5	55.2588
66	10.6	55.4201
100	10.7	54.7248

Table 4.4: Median values of Resonant frequency and isolation loss for different surface patterns with 0% and 100% 2x2. Beam surface fixed and dielectric surface varying

For better clarification median value of 25% and 66% are taken and plotted. Table 4.4 shows the median results.

Though the values of 66% and 25% overlap, when we take table 4.3 into account we can see a linear behaviour for resonant frequency with respect to surface pattern nature. Surface pattern nature here is defined as the area wise percentage of 2x2 present in the surface. 0% to 100% there is a resonant frequency change of 0.3 GHz and isolation loss of 0.1dB. When we compare 25% and 66% their resonant frequency comes between 0% and 100% but their isolation loss is higher by 1dB. Values in table 4.1, 4.2 and 4.3 are used to find median (table 4.4) and a line plot is plotted on figure 4.3 as we can see the resonant frequency increases linearly from 0% to 100% with a 0.1GHz change. Isolation loss for 25% and 66% are higher than 0% and 100%. From this result we can say that surface roughness with pattern variation can have GHz variation in resonant frequency but on isolation loss more than the percentage variation 2x2 spike positions on the surface has impact. This becomes obvious when we see in table 4.1 and 4.3 for different patterns we are getting different isolation loss whereas resonant frequency remains almost same. In other words if we compare a 2x2 spike which is on the corner of the surface and on the middle of the surface there will be a definite change in isolation loss but resonant frequency need not change. It also shows that a mixture of 1x1 and 2x2 pyramids has higher isolation loss.

In figure 4.2 a box plot of isolation loss is shown. Median values are obtained from this box plots. Box plot of resonant frequency is not plotted since its values repeats more often.

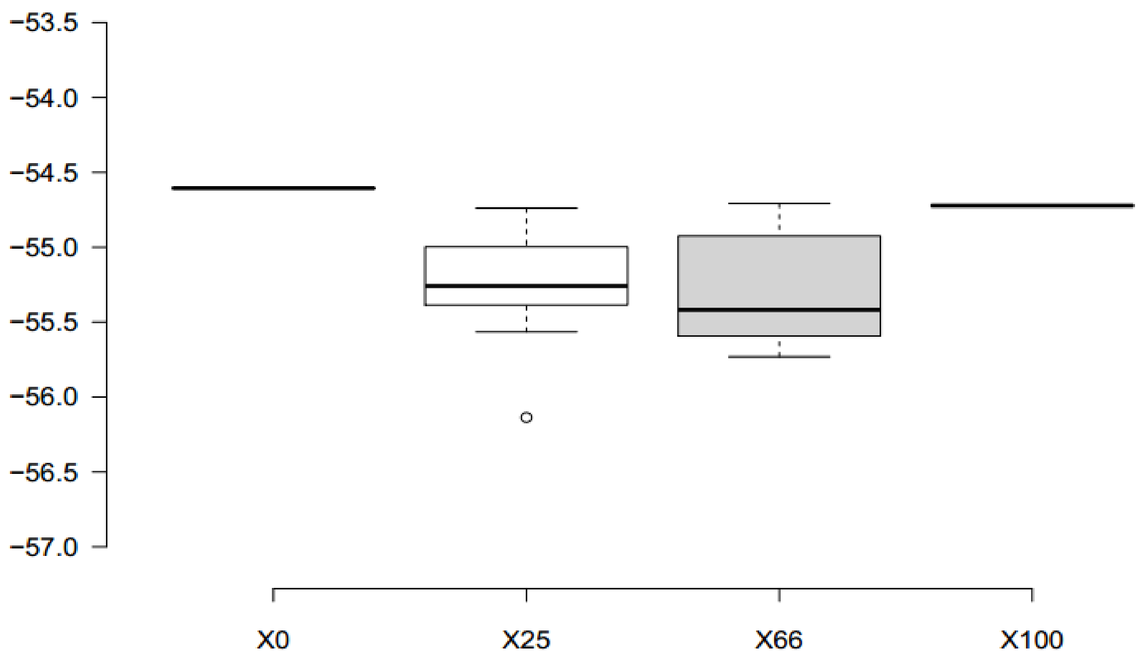

Figure 4.2: Box plot of isolation loss. beam surface fixed and dielectric surface varying

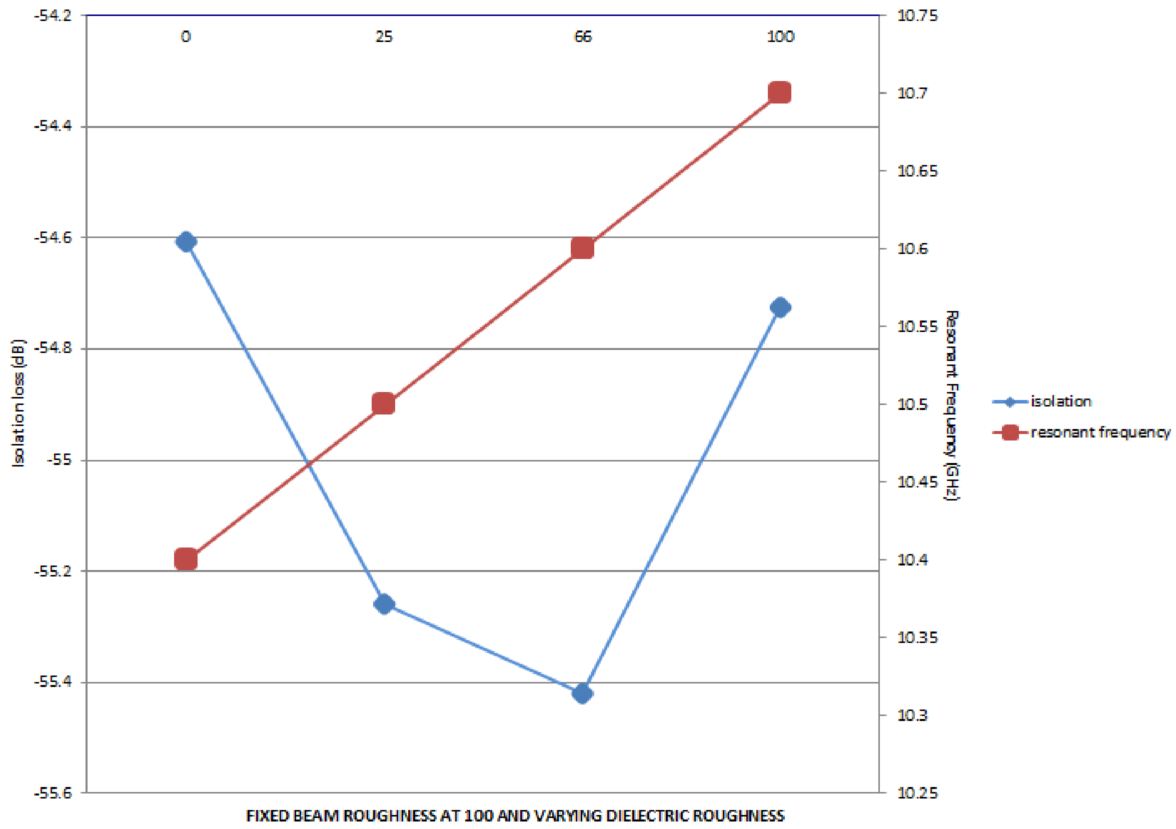

Figure 4.3: Line plot of above median table with isolation loss in left y axis, frequency on right y axis and percentage variation on x axis

We were unable to find a proper variation with beam surface roughness varying. Their results are tabulated in 4.4, 4.5 and 4.6.

Percentage	**Resonant Frequency (GHz)**	**Isolation loss (dB)**
25_1	10.6	-54.88625716
25_2	10.6	-55.59799341
25_3	10.7	-54.29027034
25_4	10.6	-55.45015806
25_5	10.8	-54.32822999
25_6	10.6	-55.0272836
25_7	10.6	-55.54734837
25_8	10.6	-55.52952971
25_9	10.6	-54.70943612
25_10	10.6	-55.28038321
Average	10.63	-55.064689

Table 4.5: Values of Resonant frequency and isolation loss for different surface patterns with 25% 2x2. Dielectric surface fixed and beam surface varying

Percentage		**Resonant Frequency (GHz)**	**Isolation loss (dB)**
66_1		10.7	-55.17408949
66_2		10.6	-55.02114818
66_3		10.6	-54.5165193
66_4		10.7	-55.16251431
66_5		10.6	-55.29654388
66_6		10.6	-55.36014865
66_7		10.6	-54.61964917
66_8		10.6	-54.89340116
66_9		10.7	-55.63683698
66_10		10.7	-55.38558275
Average		10.64	-55.10664339

Table 4.6: Values of Resonant frequency and isolation loss for different surface patterns with 66% 2x2. Dielectric surface fixed and beam surface varying

Percentage		**Resonant Frequency (GHz)**	**Isolation loss (dB)**
0%		10.7	-54.85191085
100%		10.7	-54.72476651

Table 4.7: Values of Resonant frequency and isolation loss for different surface patterns with 0% and 100% 2x2. Dielectric surface fixed and beam surface varying

%	**Resonant Frequency**	**Isolation loss**
0	10.7	54.8519
25	10.6	55.1538
66	10.6	55.1538
100	10.7	54.7248

Table 4.8: Median values of Resonant frequency and isolation loss for different surface patterns with 0% and 100% 2x2. Dielectric surface fixed and beam surface varying

For better clarification median value of 25% and 66% are taken and plotted. Table 4.4 shows the median results

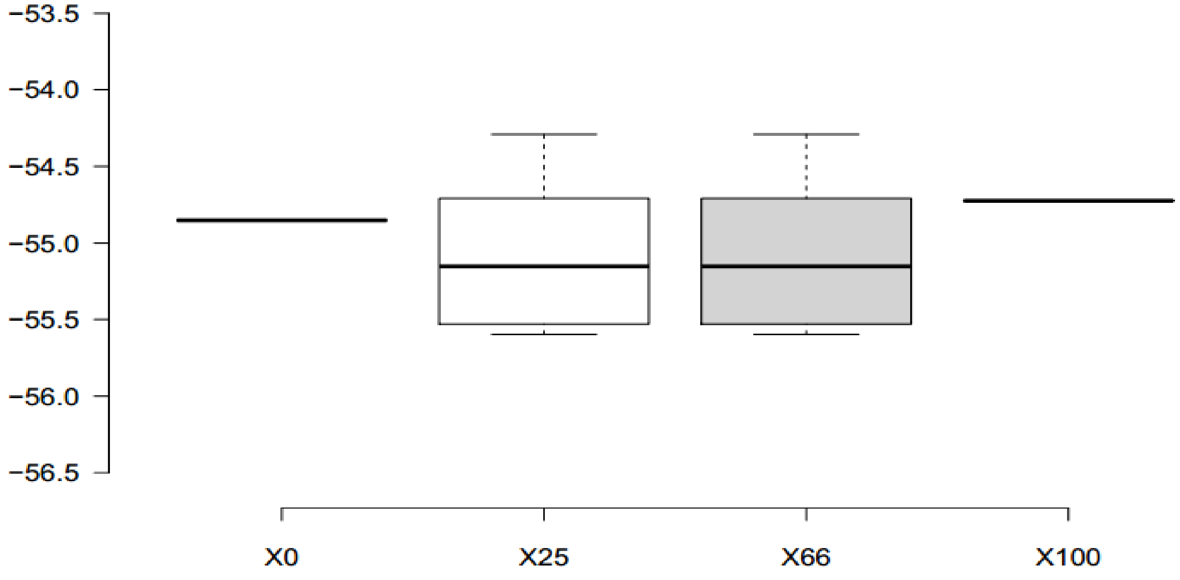

Figure 4.4: Box plot of isolation loss, dielectric surface fixed and beam surface varying

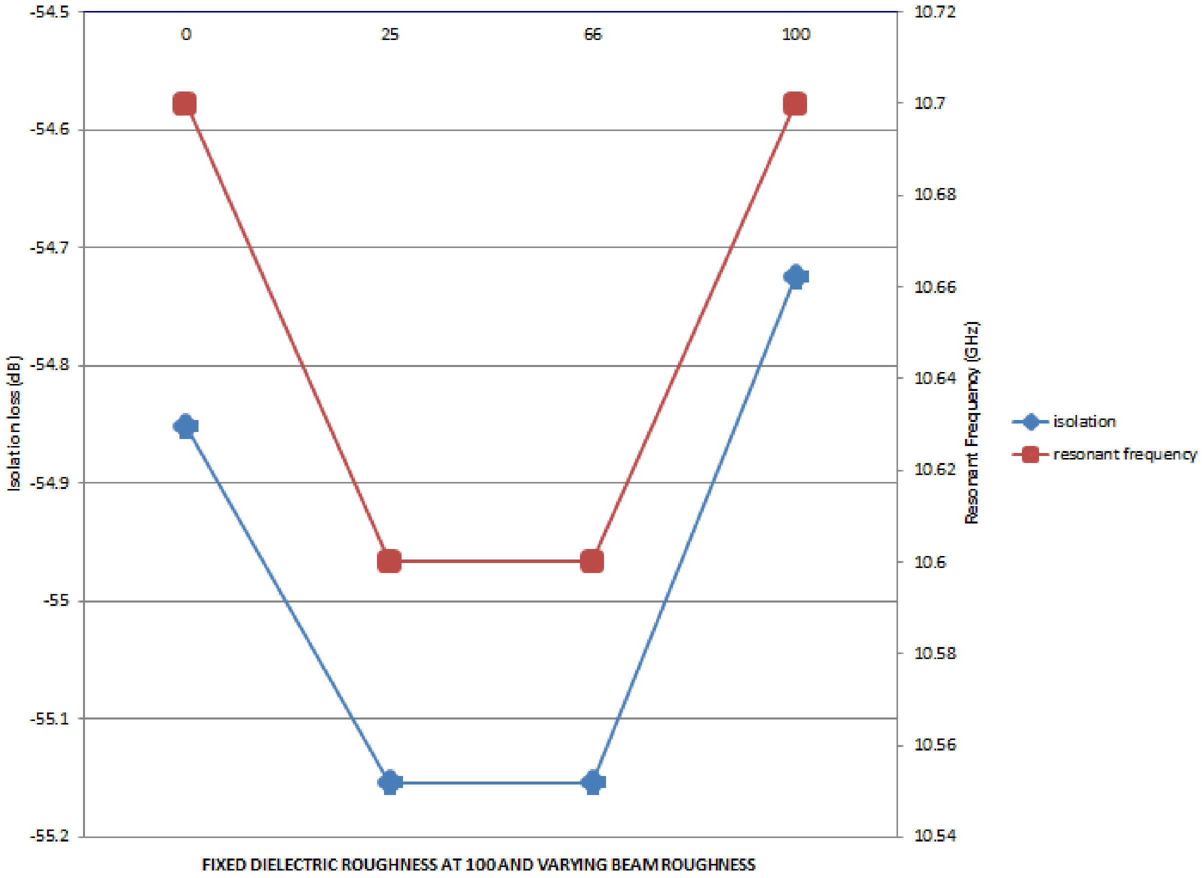

Figure 4.5: Line plot of above median table with isolation loss in left y axis, frequency on right y axis and percentage variation on x axis

Boxplot in figure 4.4 is used to obtain median values of 4 configurations

As we can see from table 4.8 and figure 4.5 0% and 100% doesn't have any change in resonant frequency. Same goes for 25% and 66% as most of their values are 10.6. From these results we can come into conclusion that surface nature of beam is nearly independent or doesn't have any recognizable characteristics.

For more credibility to the variation in the resonant frequency and the isolation loss of figure 4.3, simulation in COMSOL is done to extract capacitance and compare it with that obtained from HFSS. Getting the same value in both software is not highly likely since it depends on many parameters that might be unique to the software. So best way to analyse this is by checking the difference in capacitance values obtained. Capacitance values are given in the table 4.9. Simulation in COMSOL is done only for fixed beam surface and varying dielectric surface.

Surface	HFSS (pF)	COMSOL (pF)
0-100	6.26	7.8740
25-100	6.38	7.9015
66-100	6.29	7.8579
100-100	6.20	7.8445

Table 4.9: Extracted capacitance values from COMSOL and HFSS for one surface in each configuration

Main difference in the table we would like to see is that of 0% and 100% since they have the highest variation in the figure 4.3. Their Delta C comes as 0.06 pF for HFSS and 0.03 pF for COMSOL.

All results we saw above are for surface roughness of 1 nm. We would like to see if this characteristic we observed holds true for other variance as well. For this purpose we shall take 5 nm as variance for all surfaces and do the same process of putting different surface patterns in the dielectric surface and fixing the beam surface at 100%.

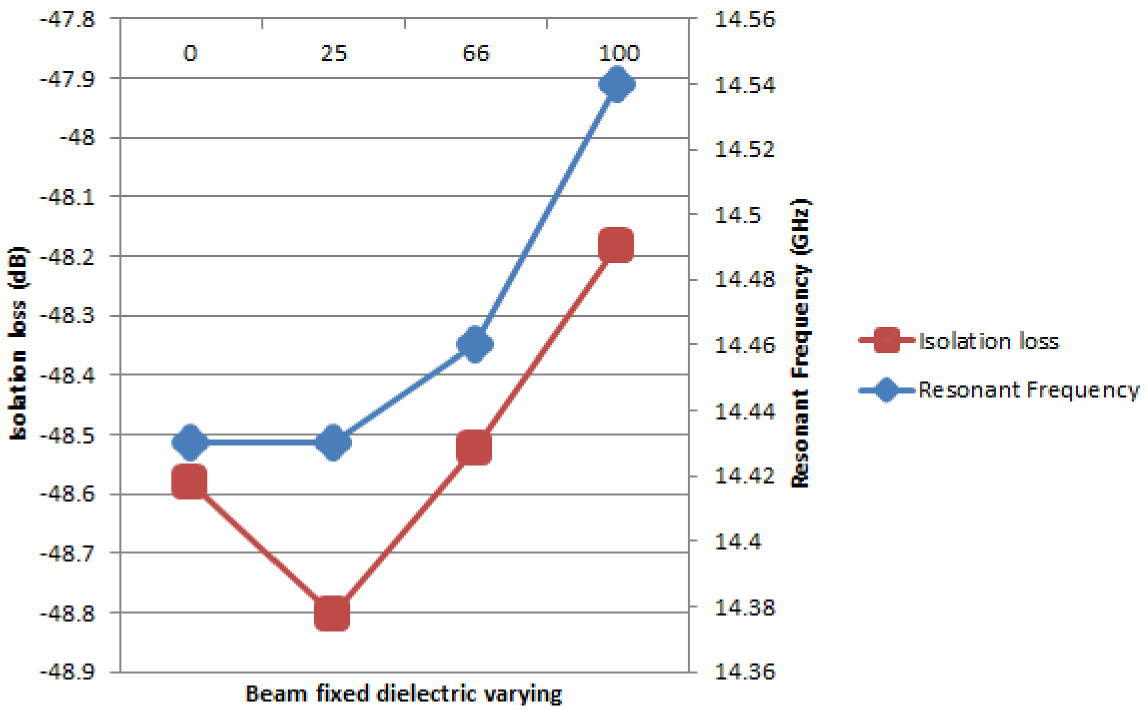

Figure 4.6: Line plot of surfaces of 5 nm variance with isolation loss in left y axis, frequency on right y axis and percentage variation on x axis

In figure 4.6 also increasing nature of resonant frequency is observed. Figure 4.7 is the isolation values for surface roughness 0 nm and 5 nm; this is without considering any variations in the pyramid base area. Isolation loss values of 0% surface is matching with figure 4.7 for 0 nm and 5 nm surface roughness.

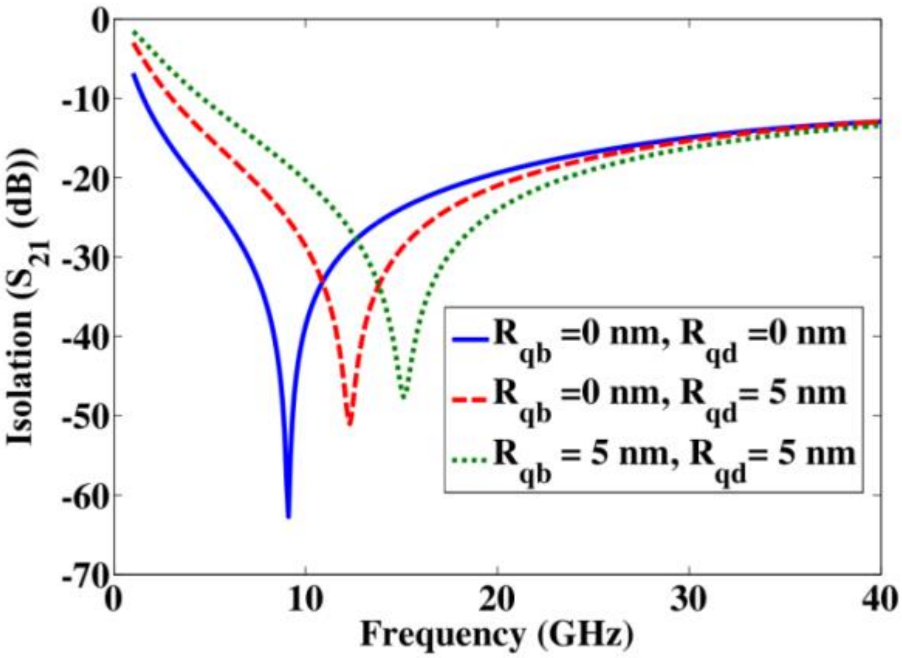

Figure 4.7: Isolation vs Frequency plot with surfaces roughness of 0nm and 5nm variance [4]

In conclusion we can say that resonant frequency increases when area wise percentage of 2x2 pyramids is varied, this can be explained by the reduction in capacitance as the 2x2 pyramids increases in the surface. Capacitance reduction in 2x2 pyramids is due to higher equivalent distance between plates of the capacitor. In other words if we consider a 0% surface and 100% surface, the former one will have higher capacitance due to lower equivalent plate distance and the latter one will have lower capacitance due to higher equivalent plate distance. This is clearer in figure 4.8, let's assume between two parallel plates a pyramid shaped dielectric surface with maximum base area (figure 4.8 a this is an extreme version of 2x2), now we will start dividing this pyramids to smaller base areas but keeping their height same. This process we will continue until all smaller pyramids approximate to form a complete smooth surface. If we compare 4.8 a and 4.8 f we can observe that its equivalent distance d has reduced this implies that 2x2 pyramid surface will have lower capacitance than 1x1 pyramid surface.

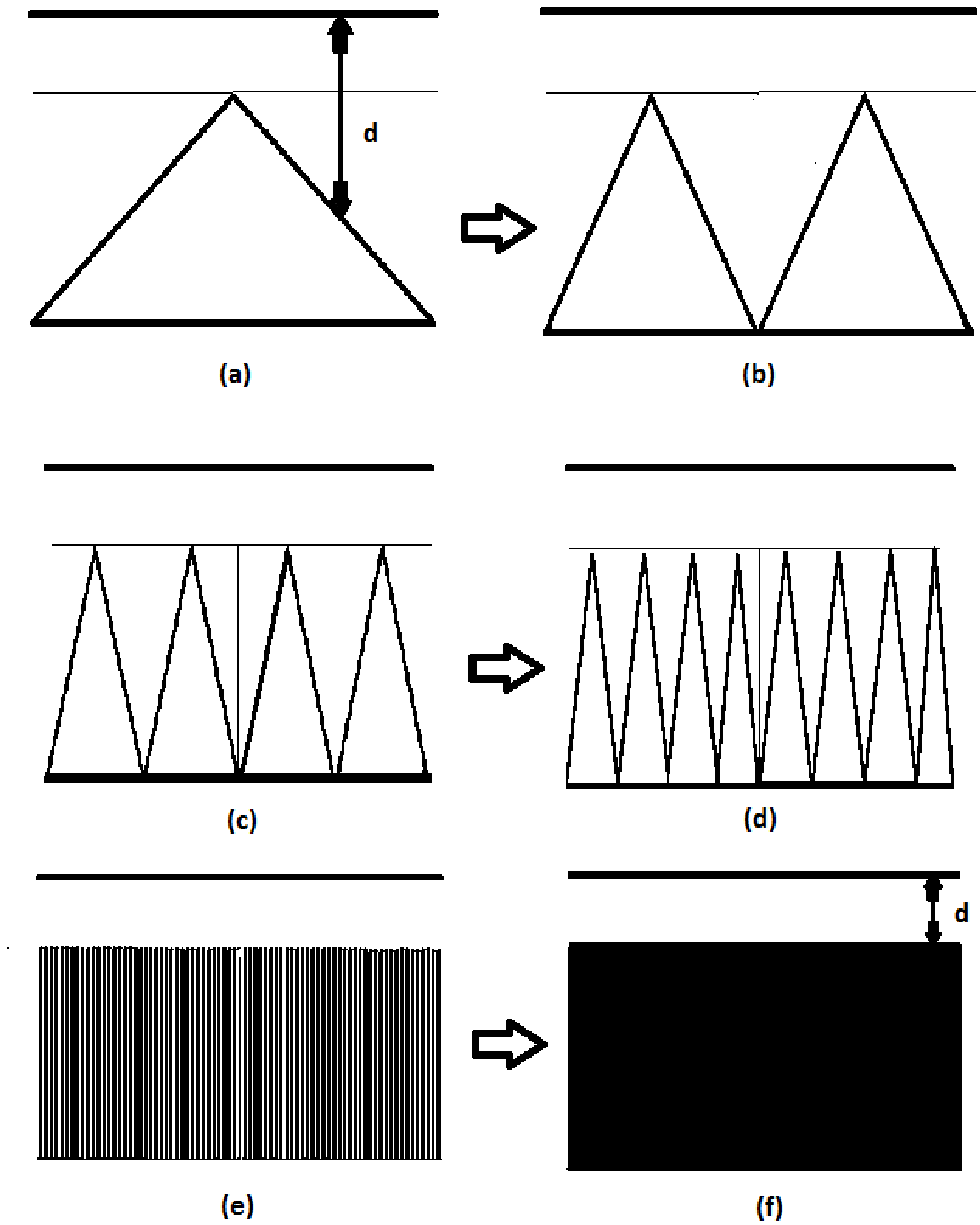

Figure 4.8: Pictorial representation of increment of capacitance from 100% to 0%.

4.3 Future Work

In this project what we mainly did is changing the surface pattern by changing the number of 2x2 pyramids present. This can be further extended by adding 3x3, 4x4 spikes but for that size of the matrix must be increased accordingly that is mere 12x12 surface cannot accommodate high number of large pyramids.

These simulations are done for downstate of the switch. The same can be done for upstate as well, and insertion loss dependency can be found.

Distance between the beam and the dielectric in reality at down state it is almost zero, but in this simulation point of contact is taken as the highest peak from both surface which is the plane at which both surface maximum pyramids meet. So to get more realistic result one could introduce destruction of some long pyramids by cutting of the top section.

REFERENCES

[1] Aishwarya Upadhyay, Kausar Ali "A Review Paper on Applications of RF MEMS Switches in Radar System." Signal Processing and Communication Technologies ISSN: 2349-6010, 2016

[2] Jung-Mu Kim and Ignacio Llamas-Garro, "RF MEMS Devices and Applications," International Microwave and Optoelectronics Conference, 2015.

[3] Sarath G, MS Thesis, "Tunable RF MEMS Capacitive Switches with Stress-resilience and Enhanced Capacitance Ratio," 2016.

[4] Sarath G., Amitava DasGupta, Deleep R. Nair, "3-D Modeling to study the impact of surface roughness on the electrical characteristics of RF MEMS capacitive switch," IEEE Journal Of Electron Devices Society, Vol 4 issue 6, 2016.

[5] Y.-P. Zhao, G.-C. Wang, T.-M. Lu, G. Palasantzas and J. Th. M. De Hosson, "Surface-roughness effect on capacitance and leakage current of an insulating film," Phys. Rev. B 60, 9157, 1999.

[6] Jeremy B. Muldavin, and Gabriel M. Rebeiz, "High-Isolation CPW MEMS Shunt Switches—Part 1: Modeling," IEEE Transactions On Microwave Theory And Techniques, Vol. 48, No. 6, 1999.

[7] A B Yu, A Q Liu, Q X Zhang and H M Hosseini, "Effects of surface roughness on electromagnetic characteristics of capacitive switches." Journal of Micromechanics and Microengineering, Vol 16, No 10, 2006.

[8] M. S. Giridhar, Prasobhkumar P. P, Ashwini Jambhalikar, J. John, R. Islam, Vedaprakash K, M Viswanatha, "Estimation of power handling limits of ohmic contact rf mems switches due to joule heating," ISSS, At Cochin, Volume: 7,2015

[9] W M van Spengen "Capacitive RF MEMS switch dielectric charging and reliability: a critical review with recommendations," Journal of Micromechanics and Microengineering, Volume 22, Number 7, 2012

[10] O Rezvanian, M A Zikry, C Brown and J Krim, "Surface roughness, asperity contact and gold RF MEMS switch behaviour," Journal of Micromechanics and Microengineering, Volume 17, Number 10, 2007.