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Analysis of Pull-in Voltage of a Cantilever MEMS Switch with Variable Beam Parameters

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Abstract— Micro Electro Mechanical Systems (MEMS) Switches have become very popular in the Electronics industry and we need to carefully select beam material for reliability and better performance. A variety of materials are available to be used as bridge material in RF MEMS switches. A cantilever beam is used to change the state and actuation of RF MEMS switch. It is made mostly using aluminum, copper or gold. This paper investigates which is the best material to be used as beam material for achieving lower pull-in voltage . The effect of different beam parameters on the RF and DC performance of MEMS series switches are also analyzed. Characterization of cantilever MEMS switches have been carried out by means of 3D simulation using COMSOL Multiphysics based on Finite Element Method [FEM]. Pull-in voltage can be reduced by carefully selecting beam material and it can further be reduced by modifying beam parameters. These parameters are also having a main role in improving RF performance of switches.

Index Terms—Micro Electro Mechanical Systems (MEMS), MEMS Switch, Pull-in voltage, COMSOL.

I. INTRODUCTION

MEMS is a technology of miniaturized mechanical and electronic elements and they are made using the techniques of microfabrication [1]. The physical dimensions of MEMS devices can vary from well below one micron to several millimeters. The types of MEMS devices can vary from very simple structures which are having no mobile elements to relatively complex electromechanical systems with multiple mobile elements under the control of complex integrated microelectronics and they are very suitable for wireless applications [2-3].

MEMS switches have been of great interest as replacements for conventional semiconductor switches [4]. RF MEMS switches have grown at a very fast rate and have many applications in wireless communication [3], microwave communication and space sub-systems [5]. In addition to this RF MEMS switches are having various applications in the field of defense, bio-medical [6], sensors [7], and actuators. The conventional FET and p-i-n diode switches in RF and microwave systems can be replaced by RF MEMS switches, because of their negligible power consumption, as well as low insertion loss, high isolation, low cost, and light weight. Because of various advantages of MEMS switches, they can be widely used in a wide frequency range, ie, from RF to millimeter-wave frequencies [8]. Typically, MEMS switches have a suspended cantilever beam. The mechanical movement of this beam facilitates electronic transmission through the transmission line. A variety of materials are available to be used as bridge material in RF MEMS switches. Some of them are Gold (Au), Aluminum (Al), Platinum (Pt), Molybdenum(Mo), Nickel(Ni), and Copper(Cu) [9]. Actuation of MEMS switches can be done using various methods, such as electrostatic, electromagnetic, piezoelectric and thermal actuation. Electrostatic actuation is most widely used because of its decreased power consumption which is near zero and linearity [10]. Here we did comparative study of performances of MEMS switches having beam materials Al, Cu, Au, Mo, Ni and Pt.

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II. THEORETICAL EXPLANATION

A. Electrostatically Actuated Cantilever MEMS Switches

In MEMS switches inorder to produce system of miniature dimensions, electrical and mechanical components are combined together on a chip. Cantilever MEMS switch is a series switch in which one end is fixed and the other end is freely suspended over space. RF-MEMS switches achieve a short or open circuit by mechanical motion of a structural element. This mechanical motion is achieved by means of electrostatic force generated due to applied voltage [11].

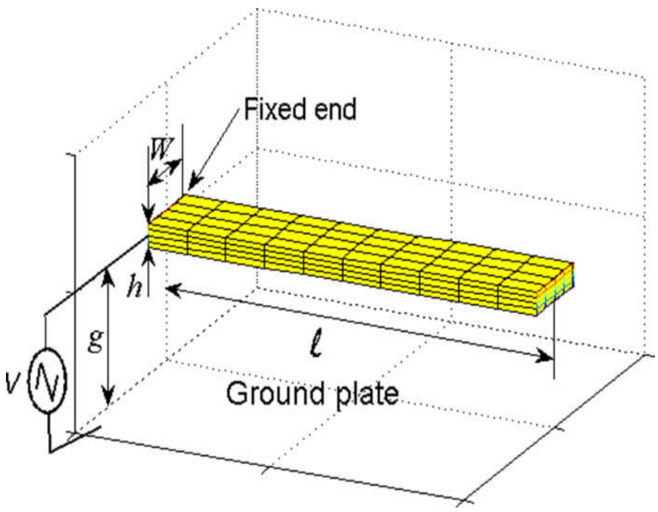

Fig. 1. Structure of Electrostatically actuated cantilever MEMS switch

Fig. 1 shows structure of an electrostatically actuated cantilever MEMS switch. In this paper, Al, Cu, Au, Mo, Ni and Pt metals have been used as the materials for beam of cantilever MEMS switch.

TABLE I

DESIGN PARAMETERS OF MEMS SWITCH

Beam Material	Beam Length[μm]	Beam Width[μm]	Beam Thickness[μm]
Al, Cu, Au, Mo, Ni and Pt	300	20	2

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The design parameter of the switch for simulation is given in the above Table 1. Inorder to realize the mechanical operation of MEMS switches the mechanical behavior of switch can be modeled using a linear spring constant, k(N/m) and it is given by,

$$k = \frac{2}{3} \times E \times w \times \left(\frac{t}{l}\right)^3 \qquad (1)$$

where E= Young's Modulus, w = width of beam, t = thickness of beam and l = length of beam [12].

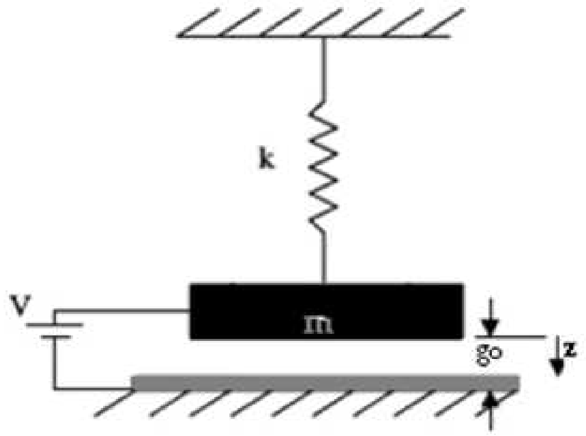

Fig. 2. Mechanical model of cantilever bridge switch

Equivalent mechanical model of cantilever bridge switch is shown in Fig. 2.

Generally electrostatic force is used for the actuation of MEMS switch. An electrostatic force is generated on the beam when voltage is applied between the cantilever beam and bottom electrode, which causes the beam to bend and finally it makes contact. The actuation voltage is given by,

$$V_{pi} = \sqrt{\frac{8kg3}{27\varepsilon oA}} \qquad (2)$$

where ε_o= permittivity of free space, A= area of beam, g=gap and V is applied voltage [12].

B. COMSOL Modeling

All kinds of engineering and scientific problems can be solved using COMSOL Multiphysics which is a powerful interactive environment based on Partial Differential Equations (PDEs). This software can transform conventional models for one type of physics into multiphysics models and these multiphysiscs models can solve various coupled physics phenomena simultaneously. Here the proven Finite Element Method (FEM) is used for solving models. Using a variety of numerical solvers, the software runs the finite element analysis together with adaptive meshing and error control. COMSOL Multiphysics (formerly FEMLAB) is a solver software package for various physics and engineering applications, especially coupled phenomena, or multiphysics based on finite element analysis. Several application-specific modules are available for COMSOL Multiphysics

COMSOL MEMS module is the main application area for designing and simulating MEMS components. We can model various MEMS devices and applications in MEMS Module, which is a collection of application modes and models for COMSOL Multiphysics.

The model of a switch is made using COMSOL. This model of an RF MEMS switch consists of a thin micromechanical bridge. When a voltage is applied across the switch, electrostatic force is generated and it causes bending of the beam. The elastic cantilever beam is an elementary structure in MEMS design. This example shows the bending of a beam due to electrostatic forces. The model uses the electromechanical interface to solve the coupled equations for the structural deformation and the electric field. Such structures are frequently tested by means of a low frequency capacitance voltage sweep.

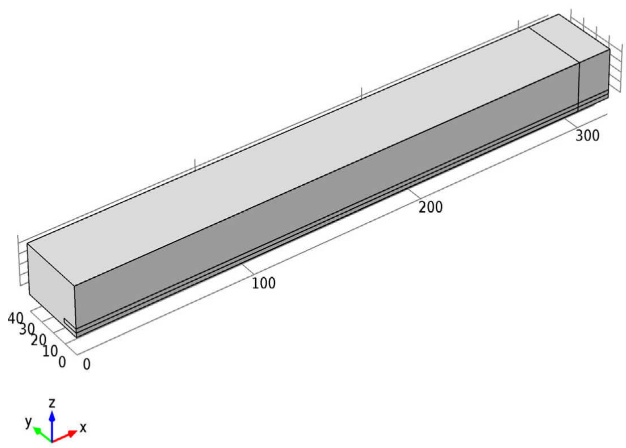

Fig. 3. Model Geometry of cantilever beam

Fig. 3 shows the model geometry of the proposed switch. Because the geometry is symmetric only half of the beam needs to be modeled. The beam is fixed at one end and free to move in the other side. The beam resides in an electrically insulated chamber which is air filled. A grounded electrode is present in the lower side of the chamber. A potential difference is applied between the two electrodes and this will cause an electrostatic force build up which will bend the beam towards the grounded plane beneath it. The model consist of a thin layer of air 20 µm thick both above and to the sides of the beam. The air gap between the grounded layer and the bottom of the beam is initially 2µm. When the beam bends due to the electrostatic force, the geometry of the air gap also changes continuously, which will result in a change in the electric field between the electrodes. The cantilever is connected to a voltage terminal with a specified bias potential, Vin. The bottom of the chamber is grounded and all other boundaries are electrically insulated. The terminal boundary condition automatically computes the capacitance of the system.

A positive feedback exists between the electrostatic forces and the deformation of the cantilever beam. The forces bend the beam and will reduce the gap of the beam to the grounded substrate. This action in turn will increase the forces. At a certain voltage the electrostatic forces will overcome the stress forces, the system will become unstable and the gap collapses. This critical voltage at which gap collapses is called the Pull-in voltage(Vpi).At applied voltage less than Vpi, the beam stays in an equilibrium position where the stress force is balanced by the electrostatic force [13].

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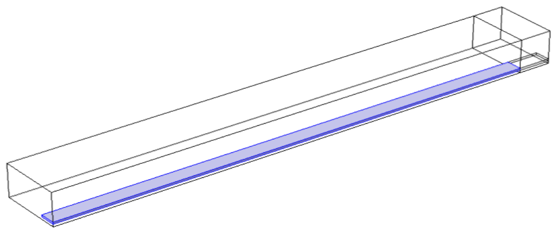

Fig. 4. Model generated using COMSOL

Fig. 4 shows model of cantilever beam switch generated using COMSOL.

III. DC PERFORMANCE ANALYSIS

Lower Vpi and stiction has become the main concern for the RF MEMS switch reliability. The material properties assume a very important role in the prevention of stiction and in decreasing Vpi. This section discusses the selection of appropriate material for the beam structure.

TABLE II

YOUNG'S MODULUS AND VPI

Metal Beam	Density, ρ[kg/m^3]	Young's Modulus[GPa]	Calculated Vpi[V]	Simulated Vpi[V]
Al	2700	70	3.78	4.3
Au	19300	71	3.92	4.4
Cu	8960	120	4.20	5.0
Mo	10200	312	7.34	8.0
Ni	8900	219	5.92	6.7
Pt	21450	168	5.26	6.0

Density, Young's Modulus and calculated Vpi of cantilever based MEMS switch is given Table 2. Different beam materials are having different density and Young's modulus as given above. It can be inferred from the table that as Young's modulus increases, Vpi also increases.

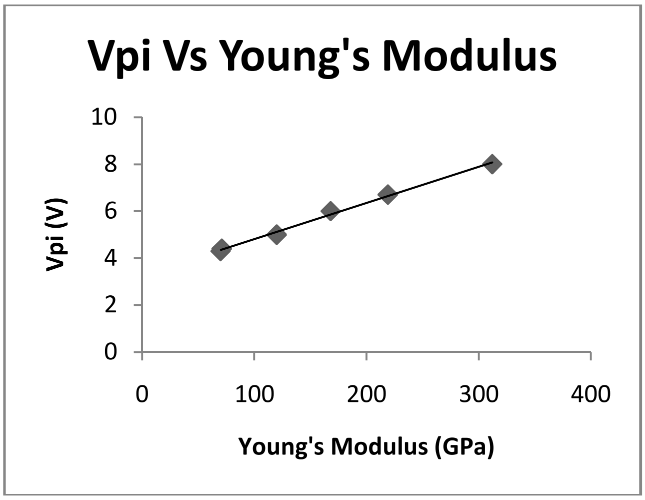

Fig. 5. Vpi Vs Young's Modulus

The selection of contact metal depends on material hardness, resistivity, melting point, and process difficulty. Material properties vary significantly based on the deposition condition of material. The lower Vpi, spring constant, effective mass and capacitance have been found in Al switch. Pure Au provides the lowest contact resistance and is most inert to oxidation but the predominant failure mechanism of pure Au contacts was found to be contact pitting and hardening damage of contact area due to repetitive contact. Hence, pure Au is not suitable for RF switch applications that require long cycling lifetime. Although, the conductivity of Au is better than Al and better conductivity implies lesser skin depth which is an important parameter for lossless signal transmission in cantilever switches [12].

Skin effect is the tendency of an alternating electric current(AC) to become distributed within a conductor such that current density is largest near the surface of the conductor and increases with lesser depths in the conductor. Since skin depth is less in the case of Au, skin effect will be dominant here. On the other hand, hard metal molybdenum handle relatively large power and do not show any stiction issue but they too have their share of problems as they were found to be more sensitive to oxidation and requirement of relatively high initial contact force. Thus, molybdenum is not suitable as contact materials. From the results obtained aluminium is found to be the most suitable material for beam. Therefore we can conclude that it is more desirable to use Al as the beam material for MEMS cantilever switches.

A. Effect of Air Gap

Here voltage is applied on the top plate of cantilever beam with different air gaps. Due to applied voltage an electrostatic force is generated in the beam and this causes bending of the beam. Factors affecting electrostatic force are beam area, applied voltage and air gap. When the beam area or applied voltage is increased, the electrostatic force increases. If the gap increases, the electrostatic force decreases and thereby increasing pull in voltage. From equation (2) we can understand that, if the air gap reduces then pull-in voltage of cantilever MEMS switch also reduces.

TABLE III

PULL-IN VOLTAGE OF Al MEMS SWITCH FOR DIFFERENT AIR GAPS

Gap [μm]	Vpi (theoretical)	Vpi (Simulated)
2	3.78	4.3
1.8	3.21	3.6
1.6	2.69	3.1

The theoretical and simulated values of Vpi for Al MEMS switch for different air gaps are given in the above Table 3. We cannot reduce the air gap beyond a certain limit because reduced air gap will lead to a compromise on the isolation and RF performance parameters [14].

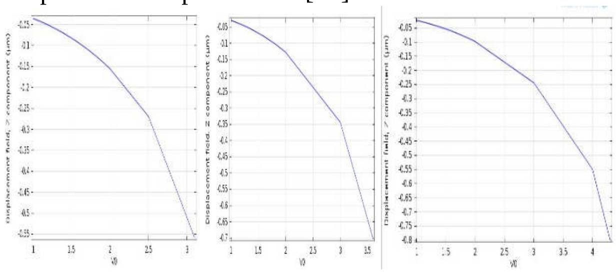

Fig. 6. Applied voltage Vs. Displacement curves at Gap =1.6, 1.8 and 2 μm for Al cantilever MEMS switch

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Fig. 6 shows the COMSOL simulated results of voltage vs. beam displacement of Al MEMS switch for air gap of1.6, 1.8 and 2 µm respectively.

B. Effect of Beam Thickness

The Pull-in voltage (Vpi) of the beam is directly proportional to spring constant k, where, k is directly proportional to Beam Thickness. Here, Al cantilever beam thickness have been varied from1.5 to 3 µm and Pull-in voltage is noted. We can see that with increasing beam thickness, Pull-in voltage also increases.

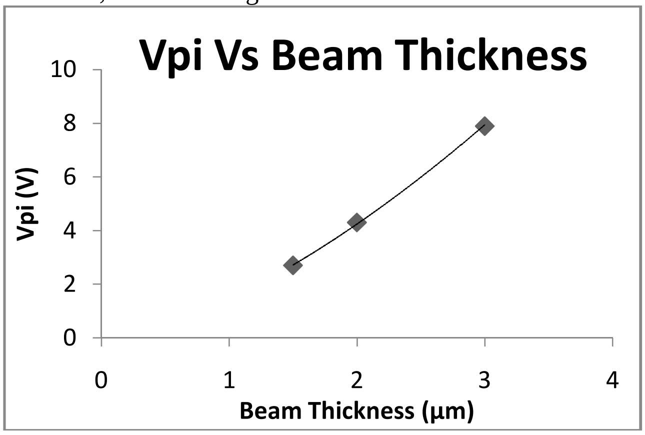

Fig. 7. Al Beam thickness variation from 1.5 to 3 µm

Fig. 7 shows beam thickness variations of MEMS switch with Al beam, keeping air gap of 2 µm which shows increase in Vpi with beam thickness.

TABLE IV
Vpi FOR Al BEAM THICKNESS VARIATIONS

Beam Thickness [µm]	Vpi [V]
1.5	2.70
2	4.3
3	7.9

Table 4 shows simulated Vpi of Al for different beam thickness.

C. Effect of Beam Length

The effect of beam length on pull-in voltage was studied and it is noted from the simulation that beam length is having inverse relation with pull in voltage. This is because beam length is inversely proportional to spring constant and spring constant is directly proportional to Vpi. Therefore increase in beam length decreases spring constant and thereby decreasing Vpi. Beam length was varied from 200 to 400 µm and result was noted.

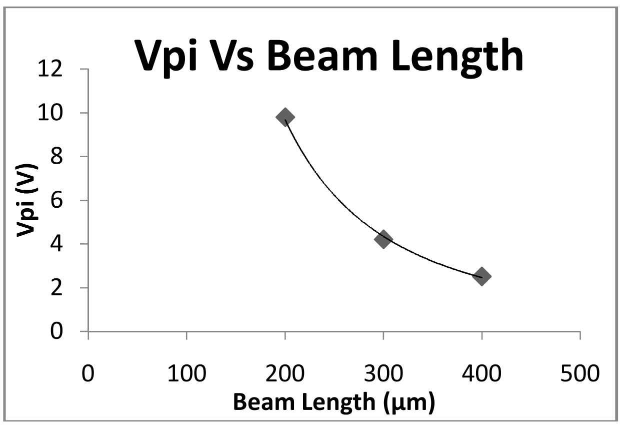

Fig. 8. Al Beam length variation from 200 to 400 µm

Fig. 8 shows beam length variations of MEMS switch with Al beam which shows decrease in Vpi with beam length.

TABLE V
Vpi FOR Al BEAM LENGTH VARIATIONS

Beam Length [µm]	Vpi [V]
200	9.8
300	4.2
400	2.5

Table 5 shows simulated Vpi of Al for different beam length.

D. Effect of Beam Width

The impact of beam width on Vpi was also studied and from the simulation it was inferred that beam width is not having much effect on Vpi.

TABLE VI
Vpi FOR Al BEAM WIDTH VARIATIONS

Beam Width [µm]	Vpi [V]
20	4.3
25	4.3
30	4.3

Table 6 shows simulated Vpi of Al for different beam width and it is seen that beam width is having not much effect on Vpi.

IV. S PARAMETER ANALYSIS

S parameter is one of the most important parameter in high frequency analysis. Consider a 2-port system as shown in the figure below.

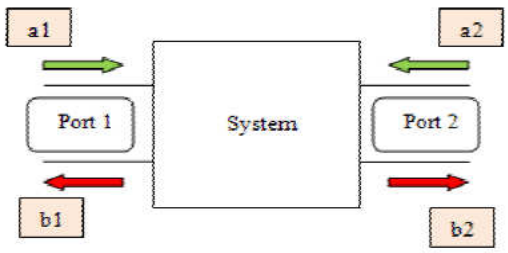

Fig. 9. Schematic diagram of a 2-port system

Here a1 = radiation wave to port 1
b1 = return wave to port 1
a2 = radiation wave to port 2
b2 is transmitted wave to port 2

For the given 2-port system, S parameter is calculated as given below

$S_{11} = b1 / a1$ & $S_{12} = b1 / a2$
$S_{21} = b2 / a1$ & $S_{22} = b2 / a2$

The performance of RF MEMS switches can be appraised from S parameter analysis. The switch proposed is designed to operate in the frequency range 1-30 GHz [13].

A. Effect of Air Gap

RF MEMS switches are having generally high isolation when compared to others. Isolation is the measure of amount of incident power that leaks through the switch and it is

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expressed in decibel (dB). S21 is the isolation of the switch when switch is in off state. In MEMS cantilever switch, isolation is given by,

$$IS = -20 \log |S_{21}| \qquad (3)$$

S21 parameter of RF MEMS switch was analyzed for different air gaps such as 1.5µm, 2µm and 2.5µm for frequency range from 1 to 30 KHz.

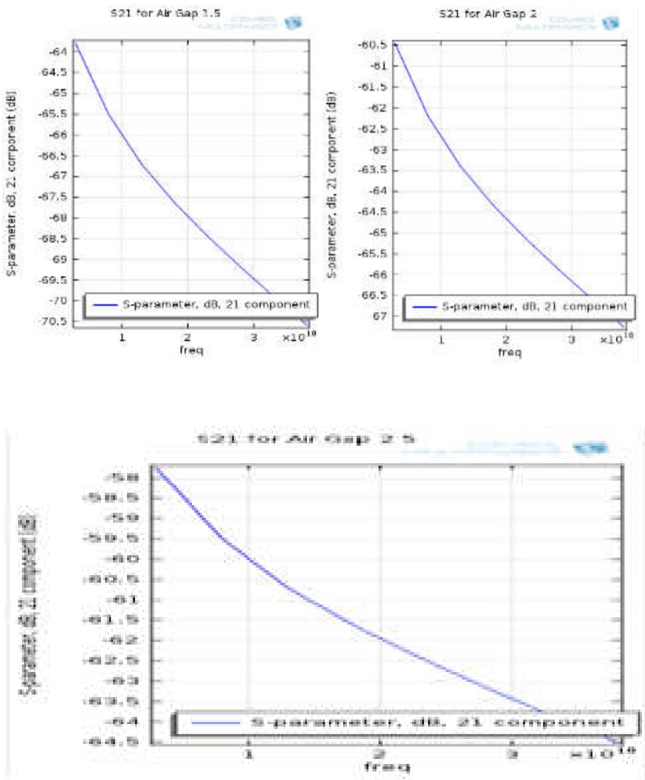


Fig. 10. Impact of Air Gap =1.5, 2.0 and 2.5 µm on S21 for Al cantilever MEMS switch

Fig. 10 shows simulated result of Al based cantilever MEMS switch for gaps 1.5µm, 2µm and 2.5µm respectively. It is seen that with increase in air gap, isolation increases.

TABLE VII
ISOLATION FOR Al BEAM AIR GAP VARIATIONS

Gap [µm]	Isolation [dB]
1.5	-70.50
2	-67
2.5	-64.5

Table VII gives isolation that can be achieved from different air gaps.

B. Effect of Beam Thickness

Effect of beam thickness on isolation was studied by analysing variation in S21 for different beam thickness ranging from 1.5 to 3µm for the frequency range 1 to 30GHz. It is observed that with increase in beam thickness, isolation increases.

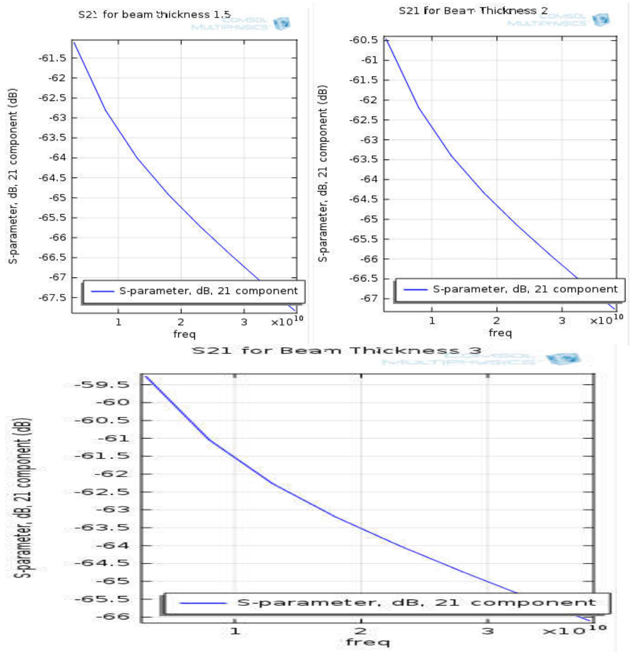


Fig. 11. Impact of Beam Thickness =1.5, 2.0 and 3 µm on S21 for Al cantilever MEMS switch

Fig. 11 shows simulated result of Al based cantilever MEMS switch for beam thickness 1.5µm, 2µm and 3µm respectively. It is seen that with increase in beam thickness, isolation increases.

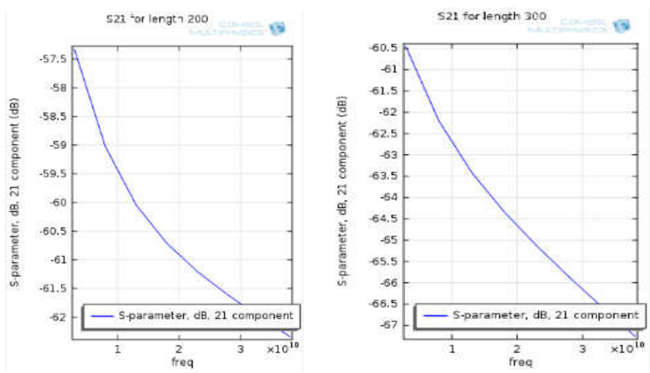
TABLE VIII
ISOLATION FOR Al BEAM THICKNESS VARIATIONS

Beam Thickness [µm]	Isolation [dB]
1.5	-67.5
2	-67
3	-66

Table VIII gives isolation that can be achieved from different beam thickness. It is also seen that beam thickness is having little effect on isolation when compared to air gap.

C. Effect of Beam Length

Effect of beam length on isolation was studied by varying beam length from 200 to 400µm for the frequency range 1 to 30GHz. It is observed that with increase in beam length decreases isolation.



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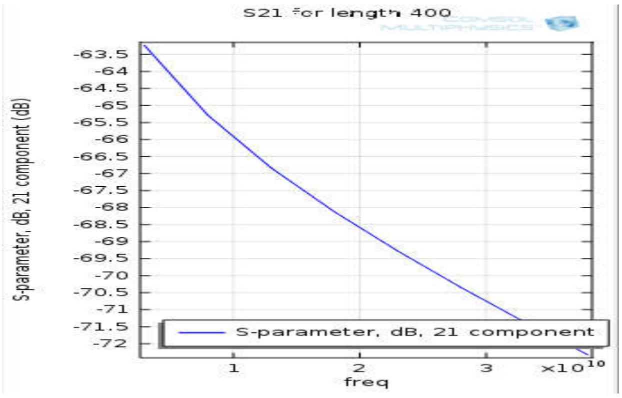

Fig. 12. Impact of Beam length =200, 300 and 400 µm on S21 for Al cantilever MEMS switch

Fig. 12 shows simulated result of Al based cantilever MEMS switch for beam length 200µm, 300µm and 400µm respectively. It is seen that with increase in beam length, isolation decreases.

TABLE IX
ISOLATION FOR Al BEAM LENGTH VARIATIONS

Beam Length [µm]	Isolation [dB]
200	-62
300	-67
400	-72

Table IX gives isolation that can be achieved from different beam length.

D. Effect of Beam Width

Isolation parameter of RF MEMS switch was analyzed for different beam width such as 20µm, 25µm and 30µm for frequency range from 1 to 30 KHz. It is observed that with increase in beam width, isolation decreases.

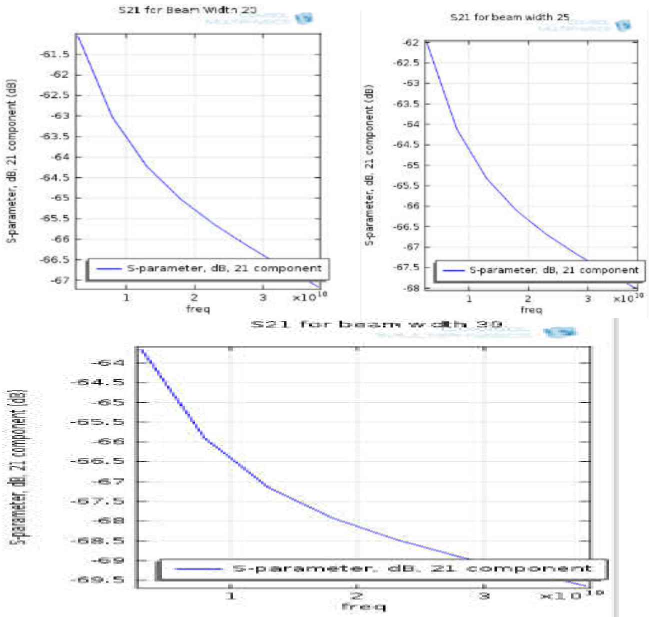

Fig. 13. Impact of Beam Width =20, 25 and 30 µm on S21 for Al cantilever MEMS switch

Fig. 13 shows simulated result of Al based cantilever MEMS switch for beam width 20µm, 25µm and 30µm respectively.

It is seen that with increase in beam width, isolation decreases. Beam width is having significant effect on isolation even if its having only negligible effect on Vpi.

TABLE X
ISOLATION FOR Al BEAM WIDTH VARIATIONS

Beam Width [µm]	Isolation [dB]
20	-67
25	-68
30	-69.5

Table X gives isolation that can be achieved from different beam width. It is also seen that beam width is having significant effect on isolation.

V. CONCLUSION

Factors on which Vpi depends are Young's modulus, dimensions of beam, spring constant (k) and applied voltage. In MEMS switches Vpi increases with increase in young's modulus. Out of several materials used for beam, aluminium is having least Young's modulus and hence the least pull-in voltage. From the results obtained aluminium is found to be the most suitable material for beam. In MEMS switches, Vpi can further be reduced by modifying beam dimensions. In MEMS switches, Vpi reduces with increasing beam area A, but we cannot increase beam area A beyond a certain limit due to the miniaturization limits of MEMS devices. Decreasing the spring constant of the beam reduces Pull-in voltage and k is directly proportional to beam thickness t. Therefore, it is understood that little bit modification on beam thickness plays a key role in the variation of Vpi. Pull-in voltage can also be reduced by decreasing the air gap because electrostatic forces over beam increases with decreasing air gap. But we cannot reduce the air gap beyond a certain limit. Vpi can also be reduced by increasing beam length. But beam width is having not much role in modifying Vpi. The lower Vpi, spring constant, effective mass and capacitance have been found in Al switch. So in MEMS switches, Vpi can be reduced by modifying beam dimensions. But decreasing these parameters adversely affects isolation of RF MEMS switches. It is seen that decreasing air gap and beam thickness decreases isolation. But when compared with air gap, beam thickness is having little effect on isolation. But decreasing beam width and beam length increases isolation. So according to our application we can modify the parameters for decreased Vpi or increased isolation. The results obtained from this work would help to refine and develop improved RF MEMS switches for a wide range of applications.

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