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Comparison of Performance Responses for Different Radio Frequency (RF) Microelectromechanical System (MEMS) Switch Structures

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ABSTRACT:
This research x-rays the effect of geometry of a microelectromechanical system (MEMS) switch on the performance of the switch. In the research a varying electrical potential from 0V to 60V was applied to the switching electrode under changing length, width and breath of the switch. This geometry parameters were varied independently and the response of the switch for each of the study is observed. And it is observed that the geometry of the switch has a significant effect on the response of the switch. The materials used for the switch is carefully made considering the effect of cost and availability of the materials used for the switch design. The effect of nature of the material is also reviewed by studying the effect of spring constant on the switch response.
KEYWORDS *geometry, microelectromechanical system (MEMS), switch.*

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I. INTRODUCTION

A switch is a device that connects and disconnects paths in a circuit. They have been found very useful in many macro and micro devices and are an essential component in the functioning of most high technology devices and industries. Switches could be designed either as macro or micro switches. In this research our study of switches will be limited to the micro sized switches whose function is stimulated by the presence of an electric potential. Switches whose function is stimulated by application of an electric potential are called microelectromechanical system (MEMS) switches. [1] defined a MEMS as "the specific sub-millimeter sized parts which need to move for the components to have electronic functionality". MEMS is a miniaturized technology whose use and importance has been appreciated in various fields of arts and science since they where first proposed at Bell's Laboratory in 1967 and demonstrated in the 1970's. Interest in this technology has been motivated by its qualities such as low insertion loss, higher isolation, low power consumption, higher linearity over semiconductor junction switches and low cost, over counterpart technologies macro technology. Figure 1 illustrate a MEMS cantilever switch.

Switches have over the years fund several applications in a wide range of specialties like wireless communications, power and electronics, biomedicine where they are used as switches and sensors for detection, selection and modulation of sound systems, connection and disconnection of electrical systems, detecting the presence and quantity of specific micro-organisms in an environment respectively. The applications of switches are not limited to just the above mentioned areas. Their applications have also been seen in many commercial and industrial applications like pressure, temperature, mass, velocity, flow, chemical composition sound, robotics, automobiles, heat pumps, transceivers, lab-on-chip, keyless entry systems, cooling electronic circuits, heat exchangers to mention a few.

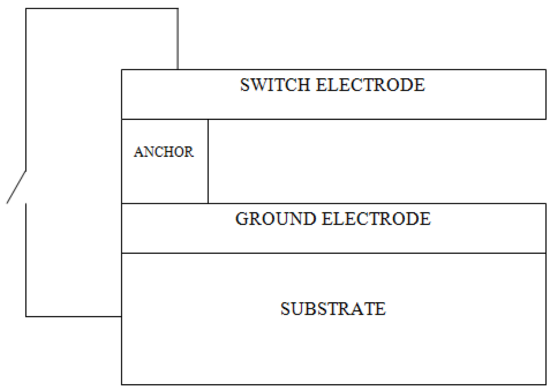

Figure 1: Switch circuit

II. LITERATURE REVIEW

Admittedly, MEMS switch design have been reported in many literatures. The algorithmic path involved in their design and simulation has already been implemented in works like [1], where they designed and simulated RF MEMS switches. In [2] the author proposed a switch with improved pull in voltage and response time. Switches have been applied in the design of reconfigurable antennas in [3]. However, the parameters studied in this research have not been reported in any reviewed literature within our reach as at the time compiling this report, the closest work to it has been reported in literature reviewed in this section.

In [4] where the author studied the relationship between length and displacement for a piezoelectric vibration energy harvester with a similar structure as the switch design proposed in this work. Several notable contributions have been made to the development of electromagnetic switches over the years. Most of these works have dwelt on principles like capacitance principles [5] and has these principles have been extensively reviewed in [6]. Other principles on which MEMS switches can be built on are pneumatic (pressure) principles, thermal principles among several other principles or a combination of one or more principles as studied in [7] where the authors combined thermal principle and capacitance principle for a hybrid RF MEMS switch actuator. Switch design architecture has also been reported in several researches literature to have diverse structure designs for how the MEMS switch should be. Some designs of switches have support on both sides, in which case it is called a fixed-fixed switch and the amount of energy required for actuation is increased. This type of design is reported by Agrawal in [8].

In the design for example as shown in [9] has a cantilever beam anchored at the bottom and runs throughout the length of the switch made of polytetrafluoroethylene, a top electrode on which it is attracted by a bottom electrode made of a gold and a contact material also made of gold. This metal to metal contact in switches is typical in most switch designs. Even though this design may have economic implication because of the complexity involved in cutting component geometry, it has a merits which is the improved design that can be made on the switch. [10] studied the reliability of multicontact switching terminal on a single cantilever. [11] research optimized cantilever switches to optimize parameters like power, pull in voltage and response time of the switch. The work also state that dimensional parameters like length, width, thickness, resistance and contact area have a level of effect on the performance of the switch. But how these factors affect the performance was not explicitly stated in the literature and have not been seen in all the literatures reviewed.

Several researchers have designed their MEMS switch with hole patterns on the surface of the switch, the reasons for this design could be to reduce the stiffness which may exist in the material, to reduce the weight of the suspended beam of switch, thus avoiding challenges in control of the switch such as striction which may lead to the beam to collapse on its base or reduce the actuation voltage of the switch, hence reducing the weight and stresses in the switch. All these reasons are pragmatic lines of reasoning although none has been proven in any reviewed literature under my review during the course of this research. A certain merit to this type of design is however that it allow for easier micromachining which has been reviewed in [12].

The basic principles guiding the performance of all RF MEMS switch under our review lie in the dimensioning of the switch's width as reported in [13], where the author identified determination of dimension of transmission line and the signal line width as important parameters to determine the signal line width.

For simplicity, the formulas that are derived to support the theory behind the performance of the MEMS switch will be based on two dimension (2D) of the cantilever switch reported in [14-15]. However the behaviour of the switch largely depends on the inherent properties of the material it is made of, the circumstance under which it is actuated and the amount of energy required for actuating it. [2] improved on the structure of a MEMS switch to improve the performance and age of the device and also reduce the sequence of activities that are usually required for fabrication. [16] Compared MEMS cantilever sensor models and proposed a MEMS sensor methodology with improved performance of a cantilever.

Most available research have used silicon technology in the fabrication of this devices as has been reported in [2-3, 5, 17-18]. In this research work however, LTCC is proposed as a design method for our designed switch fabrication. A typical LTCC model consists of dielectric tape, connecting vias, external and internal conductors and passive components which are in-cooperated into the circuit as buried or surface components in two or three dimensions. MEMS switch have been fabricated using various printing techniques, for instance [19] used the printed circuit board (PCB) to develop a MEMS switch for microstrip array antenna.

Conversion of electrostatic force to mechanical force

Under normal conditions, a well designed switch will remain in a suspended state making clear separation from the ground electrode. When a positive electric potential is applied to the switch lead, it excites it and may cause it to deflect towards the ground electrode, attempting to collapse on it. There are several ways by which the switch can be exited as proposed in [20]. The relationship between the electrostatic potential and mechanical response of the switch is given in equation below.

$$F_e = \frac{V^2}{2}\left(\frac{\varepsilon\varepsilon_0 A}{\left(g+\frac{t_d}{\varepsilon_r}\right)^2}\right)\mathrm{N} \qquad 1$$

The electrostatic force acting on the switch beam will cause the switch beam to deflect. This has several implications on capacitance $Q = CV(\text{Columb})$ that will be generated in the dielectric between the switch and the ground electrode and this effects have been studied in [5], [12], [21-23]. The energy stored between in the dielectric is given as the electrostatic energy stored between the electrode is derived in [14] as

$$\mathbf{W} = -\frac{1}{2}\mathbf{CV}^2 = \frac{\varepsilon_0 \mathbf{A}\mathbf{V}^2}{2\left(\mathbf{d}+\frac{\mathbf{t_d}}{\varepsilon_r}\right)}\ \textbf{Joules} \qquad \mathbf{2}$$

[6] identify actuation voltage, storing force, length of film and thickness of film as important factors that affect the performance of a capacitance. It is pragmatic to assume that this factors as well may affect the performance a switch given that they are essentially same structures performing functions specific to their application. In [24] the authors demonstrate the amount the effect of capacitance over increased length of suspended film. Another factor that could worth mentioning is the fringing fields that is generated given that it could be lost to the environment. Also the nature, of the surface between the beam and the material and environment in which the switch is operated can also greatly impact the performance of the switch. These factors will not be discussed in this thesis, however is worth noting as factors that affect the performance of the switch and when referenced would serve as useful materials in understanding the concepts or an RF MEMS switch.

III. MATERIALS AND METHODS

The switch design will be made using four three dimension simple structures, namely, triangle, rectangle, a trapezoid and an irregular rectangle shaped structures with same length and base width but different surface areas. The area is shown in Table 1. The philosophy behind this choice is to remove complexity in the implementation. The structures are shown in Figure 2.

A 3D model of MEMS switches will be designed and simulated to study the response of the switch to different actuation voltages. Different geometries will be designed with the intention to find the geometry with the best response under the defined material and actuation conditions. The results will also be calculated on by normal calculation using few lines of code and observations will be made to know how much the simulation result vary from the calculated result.

This work intends to analyse the several factors that affect the performance of a RF MEMS switch. The work will study these performance characteristics by varying the dimension properties of several structures as well as their shape and their responses will be studies under several voltage levels. A simulation of these structures under the varied voltages will be performed.

A gap that exist in research is the effect of geometry of a MEMS device, as it has for long been neglected or not been studied. To this effect, this research is motivated to study the how different switch geometries will respond to changing respond to changes potential difference that will be applied to it. The study of MEMS switches has several significances on the performance of RF equipments. A good switch design could be used to regulate power supply into or out of the transmission equipment. They also serve to separate wanted signal from unwanted signals in the transmitter and receiver, hence serving as a filter.

A. Contribution to knowledge

i. Study the effect of geometry of a cantilever switch on its deflection performance. This will be done using four geometries each with fixed horizontal length along and width of the switch. The thickness of the switch will not be studied as it has a direct bearing on the spring constants equation, thus indicating a linear relationship.

ii. Study the relationship between the rates of actuation of a switch when a potential difference is applied to it.

B. Choice of materials for the design

The efficiency of a switch depends on the type of material that is used to manufacture it. This is because the parameters that determine its speed such as its stiffness and its durability are largely a factor of the elasticity among other factors that are inherent properties of the material the switch is made. To this end, it is essential to choose materials to be used as switches carefully to ensure optimum performance of the switch. It is essential that optimality in performance of the switch be compared with economic performance during the material selection process. In this research three materials are used for the switch design as explained below.

i. Top electrode: This is the mobile part of the switch that serves to turn on and off the switch. It serves as top electrode in the switch device. The shape of this part of the switch could be of various shapes, and in this research work will be designed into various shapes to determine how the responses of the shapes when activated. The switch beam will be made of a metal electrode to allow for attraction of the beam with the bottom electrode.

ii. Bottom electrode: The bottom electrode is an immobile part of the switch. It serve as a means of attraction with the mobile part by generating electromagnetic field between the electrode and generating capacitance with the material between the electrodes serving as a dielectric.

iii. An anchor: The anchor is a nonmetallic material and serves to hold the top beam and the bottom beam to the switch substrate and also create a gap between the top beam and the bottom beam/ substrate. Thus allowing for monitoring of the top beam to move over a distance before making contact with the bottom electrode.

iv. A substrate: The substrate serves as a base for the entire switch where the switch is expected to deflect towards.

The choice of these materials is based on performance prediction from the values as compared to other devices and also for economic reasons. All the switches also consist of a ground electrode with dimension $200e-6 \times 300e-6 \times 50e-6$ and a substrate $200e-6 \times 300e-6 \times 100e-6$ and an anchor $50e-6 \times 50e-6 \times 150e-6$. (use equation editor)

Table 1: Area of the switching electrode

Material	Rectangle	Triangle	Trapezoid+ Rectangle	Irregular Rectangle
Aluminium	3.9000e-08	2.8500e-08	5.5000e-08	5.4750e-08

C. Structure of design

The switches where designed to be of varying geometry in three dimension (3D). The geometries are triangular prism, rectangular prism, trapezoidal prism and an irregular prism. The choice of a 3D structure is motivated by its simplicity and their potential for wide array of applications, true reflection of most practical devices and their simplicity in structure which can be found in most practical applications like those mentioned earlier.

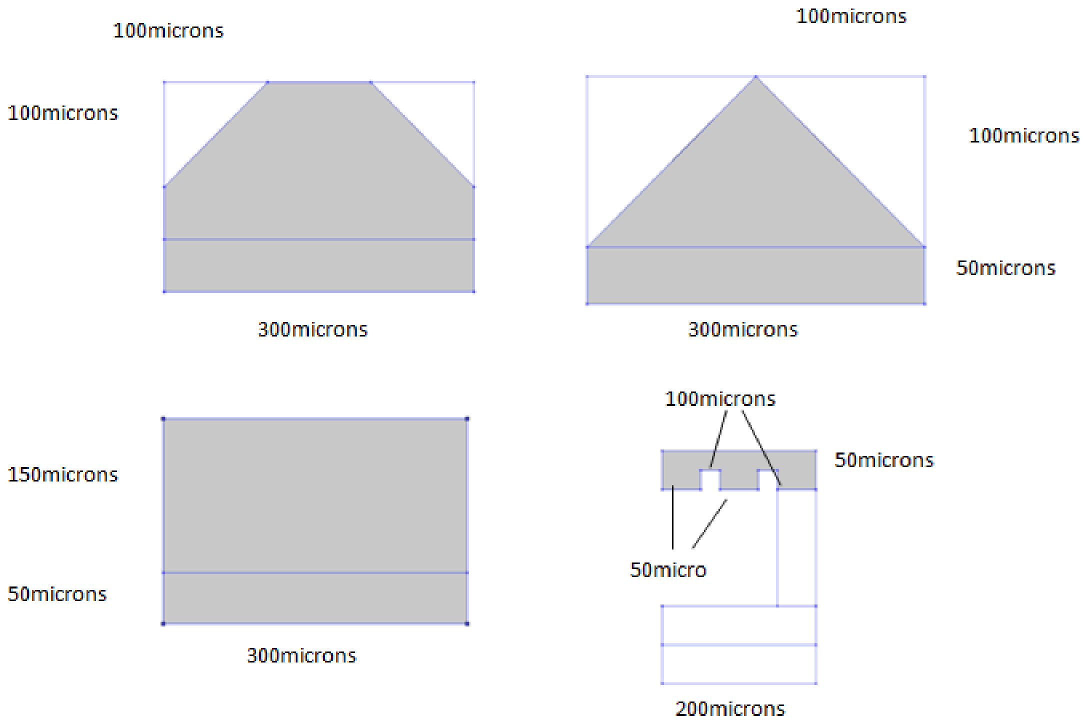

Figure 2: 2D diagram of switch structures under study

Five assumptions where made during the design, namely, that every region of the switch is smooth and is not under the effect of striction, that the equations assume the plane geometric area of the switch and does not pay attention to variation in cross sectional area of the geometry. This assumption has been used in works like [2] to calculate the performance of the switch., effects such as fringing fields and other environmental factors that may inhibit the performance of the switch were not considered., the applied potential difference is distributed on the switch evenly and finally, the study is done with same material and each material returning its inherent material property for the chosen geometry. It is essential to keep this parameters constant for all the structures for the following reasons

First, because varying them has economic consequences, a change in surface area of the material for the different structures may not result to fairness for the manufacturer. Another reason why this parameters should not be varied is because by varying them will produce variations that will not be captured by our proposed formulas in this research, finally this parameters have direct consequence on the performance of any device, for example a material with large thickness will have less deflection than those with less thickness, also a longer material will generally feel easier to bend as compared to those with shorter length, all of these can be proven by basic theories in mechanics. The parameters that will be varied will be the width of the structures. Finally the inherent material properties of a material cannot be altered else they are no longer the material.Figure 6 below represent the area and structural dimensions of the 3D structures.

IV. RESULTS

Table 2: Displacement for a Rectangular Switch

LENGTH			DISPLACEMENT			
Voltage/Length	10	20	30	40	50	60
150	9.62E-11	3.85E-10	8.66E-10	1.54E-09	2.40E-09	3.46E-09
300	1.91E-10	7.65E-10	1.72E-09	3.06E-09	4.78E-09	6.89E-09
450	2.82E-10	1.13E-09	2.54E-09	4.52E-09	7.06E-09	1.02E-08
600	6.25E-10	2.50E-09	5.62E-09	1.00E-08	1.56E-08	2.25E-08

BREADTH

Voltage/Thickness	10	20	30	40	50	60
50	2.43E-10	9.72E-10	2.19E-09	3.89E-09	6.07E-09	8.75E-09
100	9.21E-11	3.68E-10	8.29E-10	1.47E-09	2.30E-09	3.31E-09
150	4.88E-11	1.95E-10	4.39E-10	7.80E-10	1.22E-09	1.76E-09
200	3.14E-11	1.26E-10	2.83E-10	5.02E-10	7.85E-10	1.13E-09

WIDTH

Voltage/Thickness	10	20	30	40	50	60
150	2.37E-10	9.46E-10	2.13E-09	3.79E-09	5.91E-09	8.52E-09
300	2.43E-10	9.72E-10	2.19E-09	3.89E-09	6.07E-09	8.75E-09
450	2.48E-10	9.90E-10	2.23E-09	3.96E-09	6.19E-09	8.91E-09
600	2.45E-10	9.81E-10	2.21E-09	3.92E-09	6.13E-09	8.83E-09

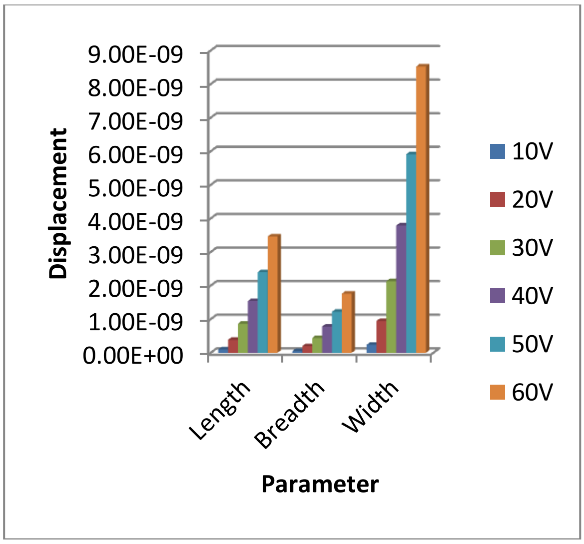

Figure 3: Comparison of changing length, breadth and width

Table 3: Simulation result for applied electric potential versus corresponding displacement

Voltage	Rectangular Prism	Triangular prism	Trapezoid + Rectangular Prism	Irregular Rectangle
0	0	0	0	0
10	1.25E-10	1.31E-10	1.23E-10	1.10E-10
20	5.01E-10	5.24E-10	4.92E-10	4.39E-10
30	1.13E-09	1.18E-09	1.11E-09	9.89E-10
40	2.00E-09	2.10E-09	1.97E-09	1.76E-09
50	3.13E-09	3.28E-09	3.07E-09	2.75E-09
60	4.51E-09	4.72E-09	4.42E-09	3.96E-09

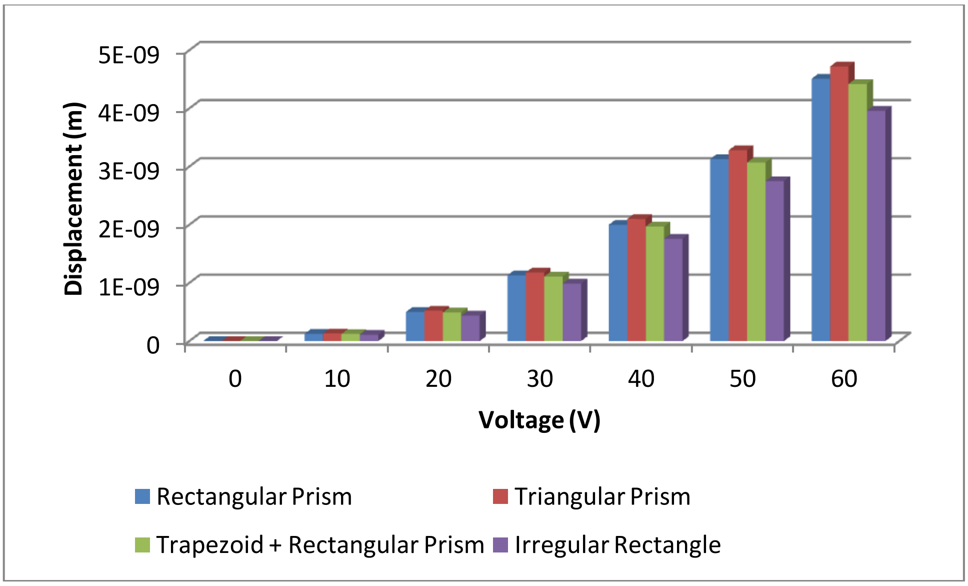

Figure 4: Comparison of different device response voltages for different geometries

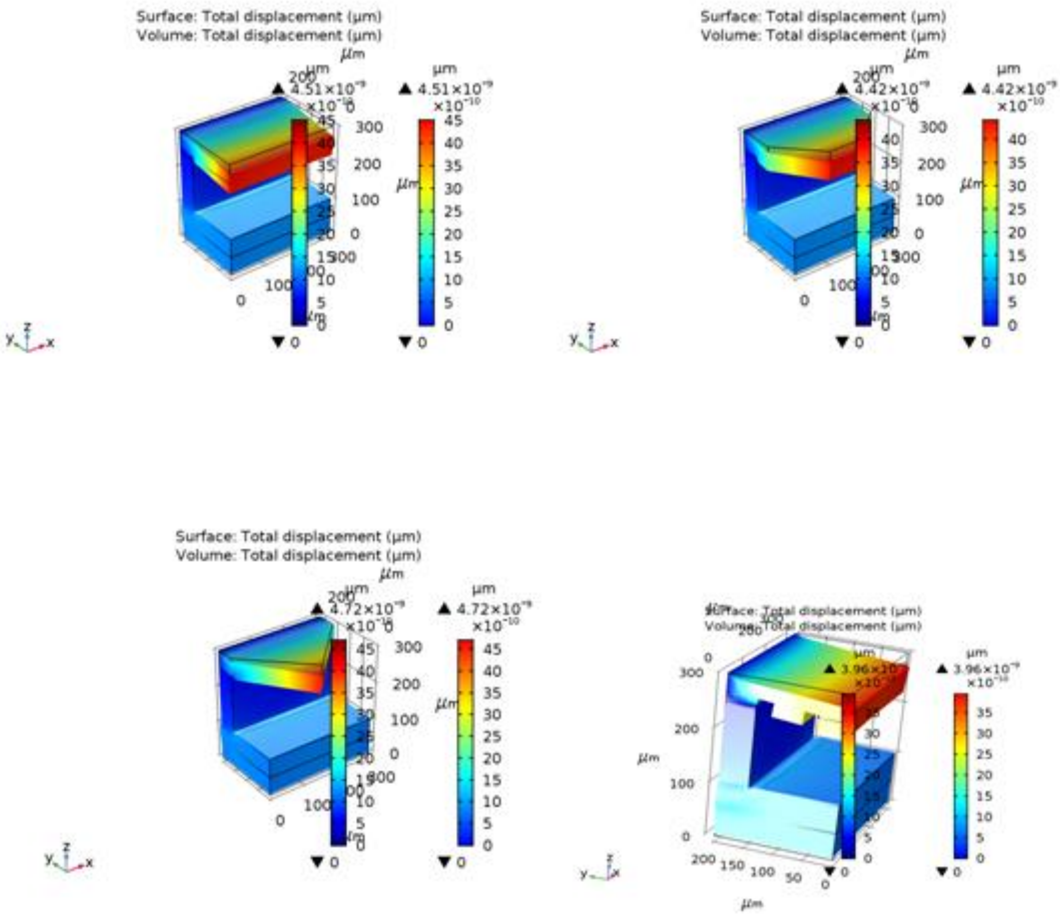

Figure 5: Displacement of switch with Height 150microns, Width 50microns, and length 300microns

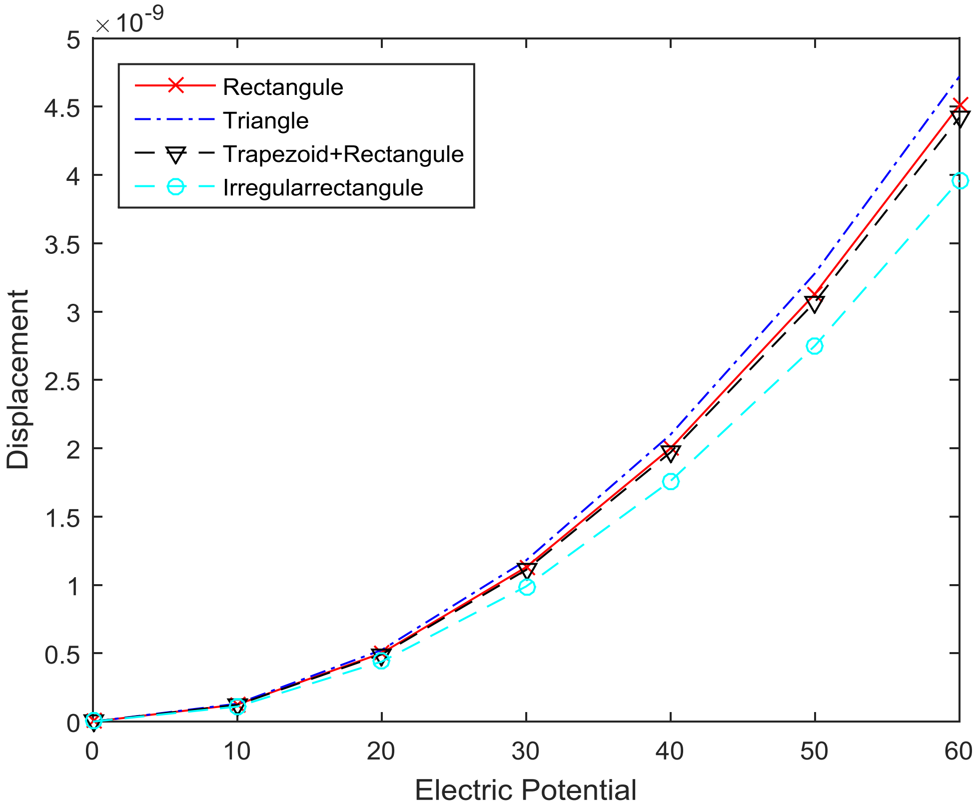

Figure 6: Simulation plot of displacement versus electric potential

The results for the sample geometry for changing width also show that beyond a given deflection, say 1/3rd of its suspended height, the width of the switch is no longer increasingly proportional to the increasing response of the switch and this can be seen in a Matlab simulation in Figure 6.

V. ANALYSIS OF RESULT

In this report, the responses of the switches are simulated and the results are compared calculated values using formula. The simulated results have been considered to be more reliable as the simulator consider more realistic factors rather than approximated in most cases grossly formulas in the formula.

By analysing the effect of geometry, it will be noticed that the width of the switch has over 62% effect on the performance of switch as compared to length which has 25% and breadth which has 13%.

It is pragmatic to think that the performance of a rectangular switch should have higher response over any of the designed switches. However, several factors affect the performances of these devices, for instance fringing field that is lost during its actuation. Other factors like spring constant could also contribute a significant factor to the performance of these devices.

More also, it can be observe from the device response that the number of geometry edges affect the performance of device. It may be observed that the switch edges between the edge of the anchor to the tip of the switch is as stated below

Table 4: Descriptive summary of the switch geometry

Geometry	Number of edges	Order of displacement
Rectangle	8	2nd
Triangle	6	1st (Most displaced)
Trapezium	12	3rd
Irregular Rectangle	24	4th (Least displaced

These responses can be explained by the behaviour of electric field, which explain that even though electric charges are evenly distributed in a metal conductor, their effects are felt most at the tip of the conductor. This can be seen as we observe that the displacement is inversely proportional to the number of edges as the switch with the host edge has higher effects disturbances along its distribution thus producing reducing the effect that should have been felt at the tip of the switch.

Being that the equations for the relationship between the MEMS switch performance are only an approximation formula and derived only for two dimensional structures, the 3D switches was taken into consideration and the equations for displacement as it related to pull in voltage and electrostatic force.

VI. CONCLUSION

From the simulated result, we can conclude that the structure of a MEMS switch has effect on its response to changing electric potential. Even though the effect is small as shown from the result. For high response where the amount of displacement is a primary criteria of measurement in a system, a triangular switch will produce the most desired result. The reason for improved displacement when the number of switch edge increase has been associated with reduced edges of the switch.

Also Matlab simulation results have shown when compared with the Comsol Multiphysics simulation that the equations commonly used for MEMS switch analysis is a gross approximation of the performance of the actual device performance.

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