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Design and Simulation of a Low Actuation Voltage Capacitive Micro Electro Mechanical Systems' (MEMS) Switch

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ABSTRACT:
In this paper we have proposed a new switch or structure for reducing actuation voltage. This switch is compared with four conventional structures considering the force range of 1uN to 3uN. We have used the ANSYS software for design and simulation for the switch parameters such as actuation voltage, collapse voltage, spring constant and resonant frequency. Small size (half of the size of other proposed materials), which can reduce the manufacturing cost, and also low-valued spring constant, which results in actuation voltage reduction, are among more noticeable features of the proposed switch.

KEYWORDS: MEMS, Switches, Collapse Voltage, Sensitivity, Fixed-Fixed Beam.

1. INTRODUCTION

The past few years have witnessed an increasing maturity of the Micro Electro Mechanical Systems (MEMS) industry. The switches can be made very small, and designed to satisfy lower actuation voltage demands.

MEMS switches can be employed in radio frequency RF circuits, and their performance could surpass other standard technologies such as FET, and PIN diodes [1]. This is due to their good linearity, low noise, low power consumption, high electrical isolation and ultra wide frequency band [2].

With respect to the large spectrum of applications, MEMS enjoy a rich variety. One of the important realms is RF (Radio Frequency) MEMS which are manned for RF integrated circuit with RF MEMS switches. RF MEMS switches commonly use mechanical movement to exhibit a short circuit or open circuit in the RF transmission line [3].

These switches have demonstrated superior RF characteristics compared to FET and diode based switches. The switch can be in series [4] or in shunt [5] with the signal path while coupling can be either capacitive [6] or metal-to-metal [7]. They are promising elements for reconfigurable circuit applications [8], and their direct compatibility with high-speed electronics makes them a low-cost candidate. There have been several demonstrations of MEMS switches used in phase shifter circuits [9], [10], and applications in reconfigurable antennas have been made feasible [11].

Technology advances and the variety of materials used in switches, creating new structures to reduce the actuation voltage. The most important factors in reduction of actuation voltage are reduction of spring constant, reduction of the gap and increase the proof-mass. Large changes in any of these factors, could adversely affect the other parameters of the MEMS switches. For example, the actuation voltage is reduced by decreasing the spring Constant, but will also reduce the reliability of the switch. Therefore these factors must be optimized.

2. MEMS SWITCH DESIGN

MEMS switches have different shapes. However, all MEMS switches have the three principally similar components: substrate, transmission line and beam [12]. The overall design of MEMS capacitive switch is shown in figure 1. This tool consists of one membrane and a beam mounted on a dielectric layer of silicon nitride, and it is connected from both ends to ground conductors using anchors. The dielectric layer is located on the central electrode and its function is preventing the beam from sticking to the central electrode.

2.1. Fixed-fixed beam structures

Although the fixed-fixed beam switches need several times higher actuation voltage than the cantilever beams, they are still in use in ninety percent of the application cases. Cantilever switches, on the other hand, present the advantage of lower actuation voltage; however, they suffer from contact stickiness due to factors like pollution. The releasing force in switches is provided by the restoring force of the spring, and since this power is lower in cantilever beams such structures are more susceptible to dirt and stick.

Figure 2 shows some samples of conventional fixed-fixed switches which are often used in MEMS capacitive switches. These beams are used in order to reduce spring constant and therefore reducing actuation voltage in MEMS switches.

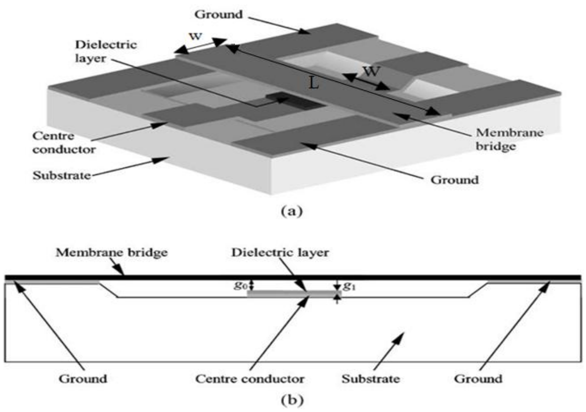


Fig. 1. Schematic diagram of a capacitive micro-machined switch: (a) a 3D isometric view of a simple capacitive switch; (b) the cross-sectional view of the switch [13]

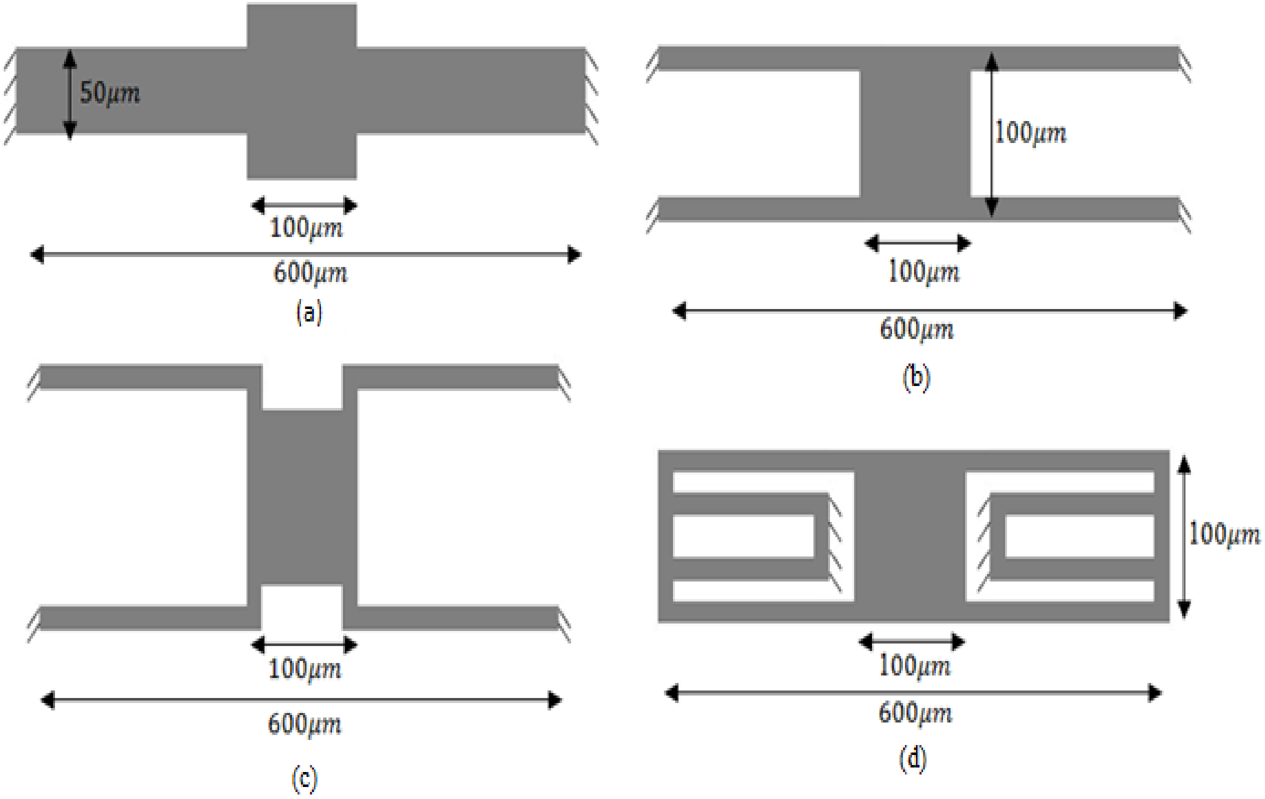


Fig. 2. Different structures of the beams: (a) structure1; (b) structure2; (c) structure3; (d) structure4

2.2. Proposed beam structure

Figure 3 shows the proposed beam structure that is used in MEMS capacitive switches. As seen, the size of proposed beam is half of the conventional models, which results in reduced weight, easier packaging and therefore lower manufacturing costs. Among other advantages, lower actuation voltage is underlined in this paper, compared to other conventional structures.

The mechanical and geometric parameters of the conventional structures and the proposed one are presented in Table 1.

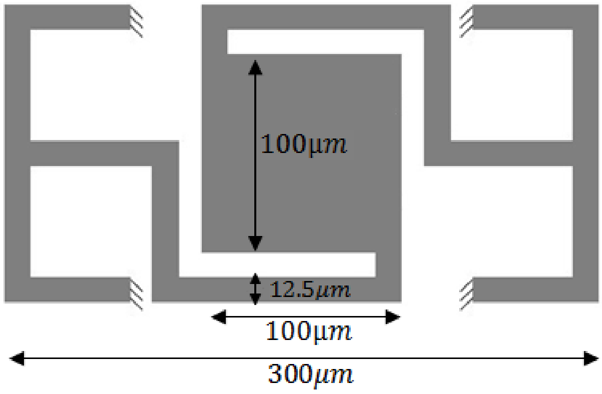


Fig. 3. Proposed beam structure

Table 1. Geometric parameters

Geometric parameters	Values
L	$600\mu m$
w	$100\mu m$
t	$3\mu m$
A(Ww)	$100\times100(\mu m^2)$
ε_0	$8.85\times10^{-12}\ F/cm$
ε_r	7.6
t_d	$0.2\mu m$
g_0	$3\mu m$
ρ_{Au}	$19320\ Kg/m^3$
E_{Au}	$80GPa$

3. ELECTROSTATIC ACTUATION

By applying a voltage between the beam and electrode, an electrostatic force is generated. This force appears on the beam. In order to approximate the force and the set of beam and electrode, a capacitor with aligned layers is used as a model.

Denoting beams width by (w) and electrodes width by (W), the capacity is obtained through equation (1),

$$C=\frac{A\varepsilon_0}{g}=\frac{Ww\varepsilon_0}{g} \tag{1}$$

where g is the distance between the beam and electrode.

Also we can calculate the electrostatic force applied to the beam using equation (2),

$$F_e=\frac{1}{2}\frac{dc(g)}{dg}=-\frac{1}{2}\frac{\varepsilon_0 WwV^2}{g^2} \tag{2}$$

where V is the applied voltage between the beam and electrode.

From equality between the electrostatic and the spring force equations, given in equation (3), the actuation voltage between the beam and electrode is calculated, as shown in equation (4).

$$\frac{1}{2}\frac{\varepsilon_0 WwV^2}{g^2}=k(g_0-g) \tag{3}$$

$$V=\sqrt{\frac{2k}{Ww\varepsilon_0}g^2(g_0-g)} \tag{4}$$

where K is the effective spring constant and g_0 denotes the initial distance between the beam and electrode.

The maximum range of beam movement from basically initial position is equal to ($g_0/3$), therefore the actuation voltage of the beam cannot take values further than a certain amount; otherwise, it would destabilize the structure.

Figure 4 shows the gap height chart according to different applied voltages. It is apparent that beyond the distance of $(2/3)g_0$ the structure will become destabilized.

Using voltage equation and gap height, we can calculate the voltage in which at $(2/3)g_0$, the structure becomes unstable, as in equation (5),

$$V_{Pull-in}=V\left(\frac{2g_0}{3}\right)=\sqrt{\frac{8k}{27\varepsilon_0 Ww}g_0^3} \tag{5}$$

This section consists of the analysis and simulation results of the proposed beams using ANSYS software. The results are compared with those of the conventional ones, in the following section.

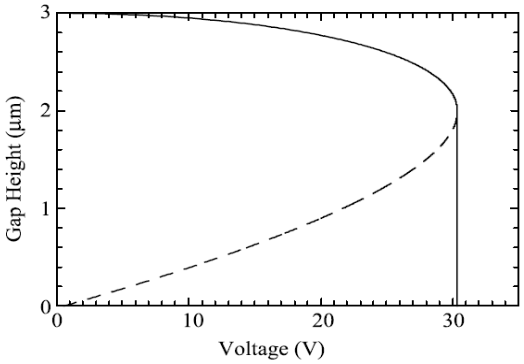


Fig. 4. Beam height versus applied voltage [2]

3.1. Spring Constant

When a beam is twisted, the gap between it and the electrode changes. Therefor the efficient spring constant of a fixed-fixed beam is obtained from equation (6):

$$K_{eff}=\frac{F}{D_{\max}} \tag{6}$$

Where D_{max} is the maximum deflection and F is the applied force over the beam.

Table 2 shows the efficient spring constant values for the conventional and proposed beams.

Table 2. Efficient spring constant values for different structures of beam

Different structures of beam	effective spring constant
Structure 1	17.73
Structure 2	8.06
Structure 3	7.19
Structure 4	5.18
Proposed beam	5

3.2. Actuation Voltage

We can calculate actuation voltage of different forces using both equation (4) and the results of simulation. Reduced actuation voltage is one of the advantages of the proposed beam compared to other conventional beams. This is clearly illustrated in figure 5.

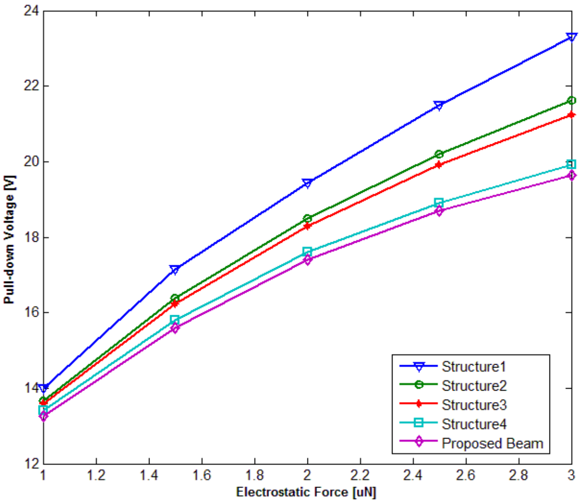


Fig.5. Diagram actuation voltage values vs. the electrostatic force

3.3. Resonant frequency and displacement sensitivity

Usually, structural and vibration analyses are performed in order to design MEMS tools, thus resonant frequency and sensitivity are deemed as two important parameters. Resonant frequency and displacement sensitivity of MEMS capacitive switches are calculated using equations (7) and (8), respectively,

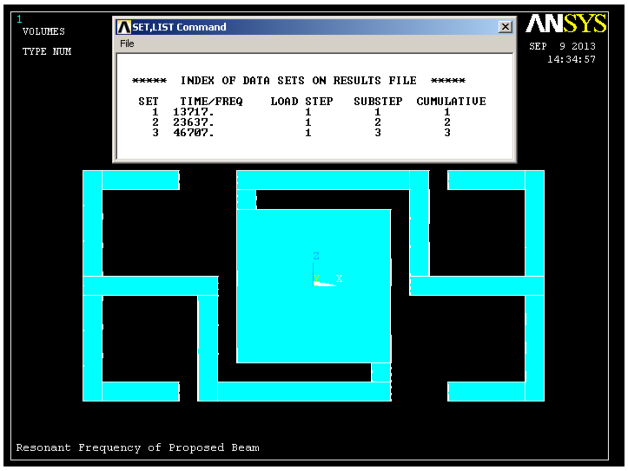
$$F_r = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}} \qquad (7)$$

$$S_d = \frac{D_{\max}}{F} = \frac{1}{k_{eff}} \qquad (8)$$

Where K_{eff} is spring constant, and m_{eff} is effective mass of the switch.

Resonant frequency and displacement sensitivity have a reverse relationship. In other words, when one is reduced the other one increases. This is why design process requires optimization of the two initially.

Figure 6 shows the resonant frequency resulted from the beam. Moreover, the values from each structure are given in Table 3. It is easily seen that the proposed beam is more sensitive than other beams.



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 *****  INDEX OF DATA SETS ON RESULTS FILE  *****

  SET   TIME/FREQ    LOAD STEP   SUBSTEP  CUMULATIVE
    1  13717.            1          1          1
    2  23637.            1          2          2
    3  46707.            1          3          3
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Fig.6. Resonant frequency obtained from the proposed beam

Table 3. Resonant frequency and displacement sensitivity for the different structures and the proposed beam

Different structures of beam	Resonant Frequency [KHz]	Sensitivity [m/N]
Structure 1	25.16	0.056
Structure 2	21.17	0.124
Structure 3	19.45	0.139
Structure 4	13.48	0.191
Proposed beam	16.49	0.2

3.4. Collapse voltage

We should recall that when we increase the voltage applied to a switch, the electrostatic force generated and imposed on the beam increases as well. Beyond $(2/3)g_0$ displacement, the rise in electrostatic force becomes higher than the spring restoring force, which makes the beam destabilized such that it collapses. The voltage at which this phenomenon takes place is named "Collapse voltage", which is calculated using equation (5). Figure 7 shows the changes in the gap distances with respect to the collapse voltages for some different structures.

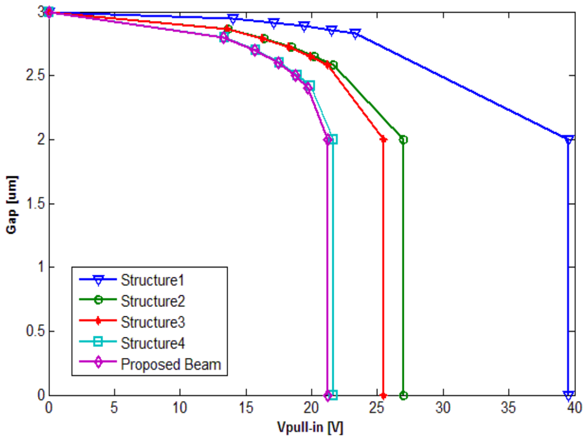

Fig. 7. Beam height versus applied voltage

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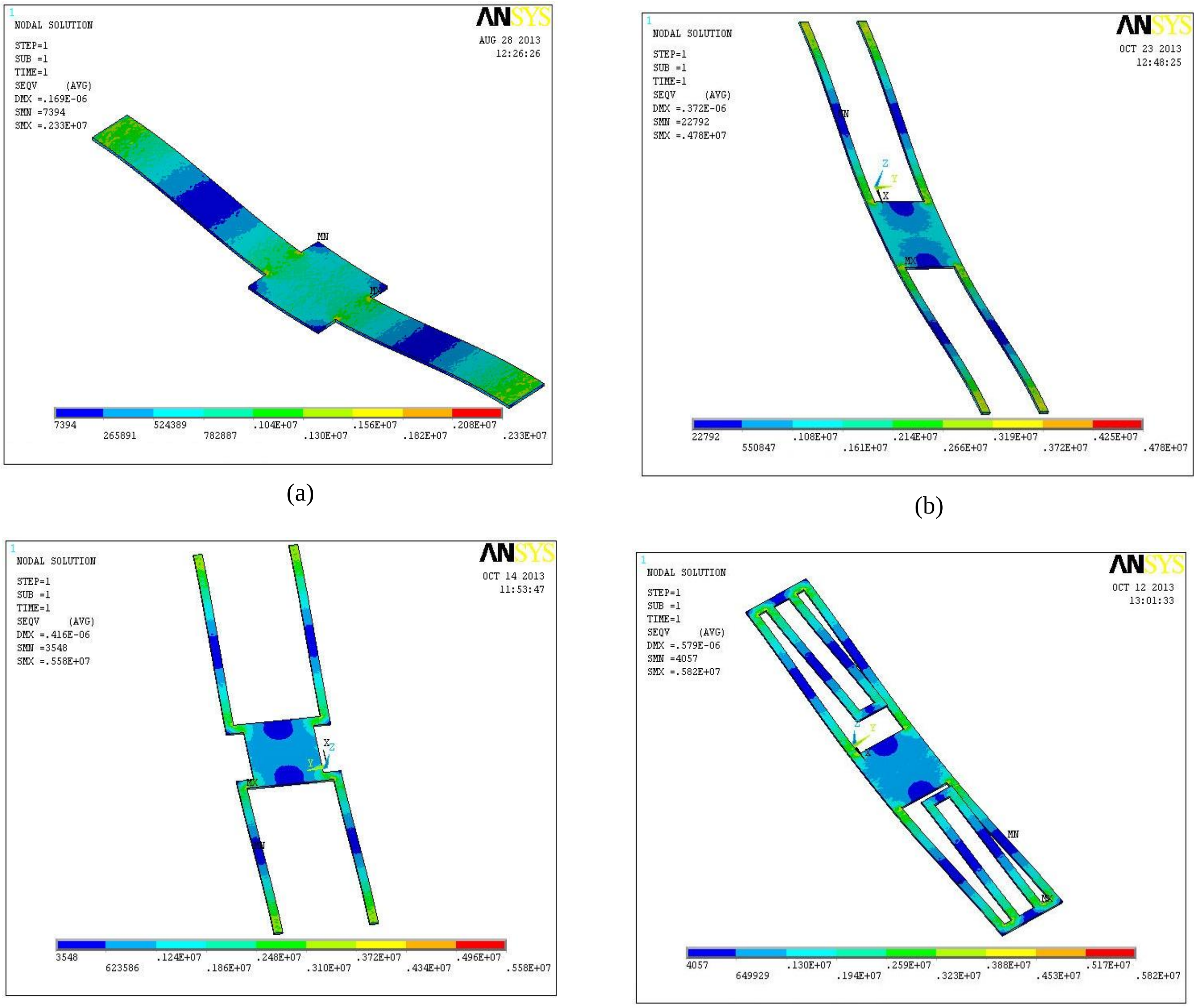
3.5. Stress

Stress is an important factor in the switch, which shows the pressure distribution on the surface of the bridge. In other words, it predicts the possible ruptures and crushes upon the bridge as the pressure rises.

Figures 8 show the stress from all structures as resulted from simulation work using ANSYS. It should be noted that in all structures the applied force to the beams is equal to 3uN.

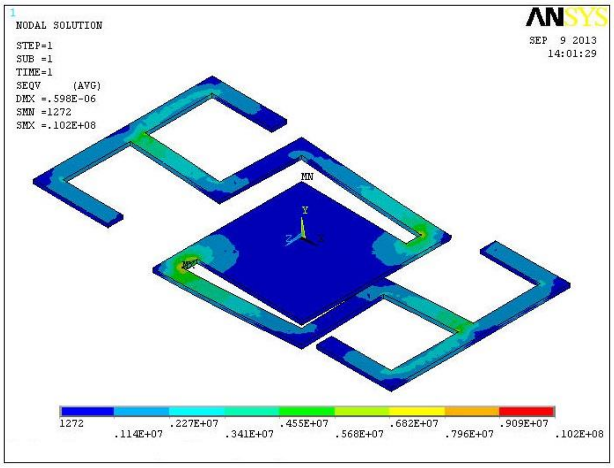


(a)

(b)

(c)

(d)



(e)

Fig. 8. Maximum stress for a force equal to 3uN applied on the conventional and proposed beams

Considering the preceding simulations, it is observed that the stress in the proposed beam is higher than other structures. To decrease part of this stress at the connection points of the beam, the arc-like curves were tried for these critical areas, as depicted in Figure 9.

Fig.9. Modified proposed beam

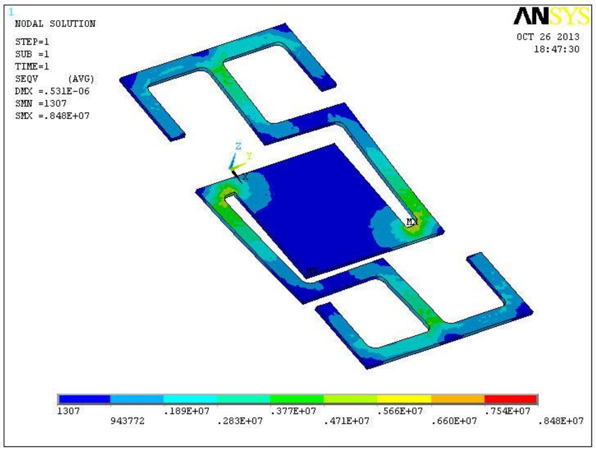


Fig.10. Maximum stress for a force equal to 3uN applied on the modified proposed beam

Figure 10 shows the maximum stress from the improved proposed beam with respect to 3uN force applied. The simulation results of both the proposed and improved proposed beams are presented together in Figure 11. It is evident that the arc-like curves bring about less stress.

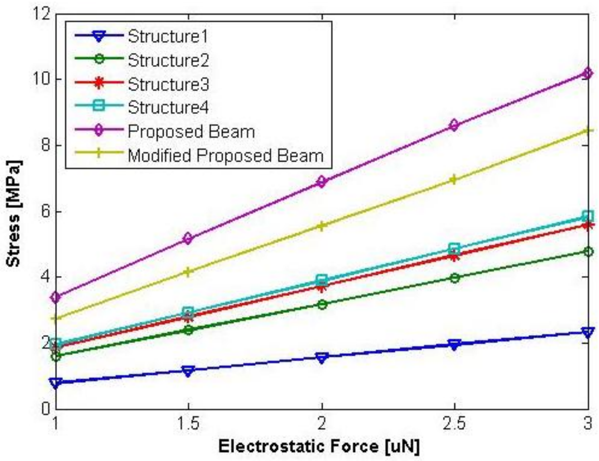


Fig.11. Diagram maximum stress vs. the electrostatic force

4. CONCLUTION

In this paper we compared some different common beams for MEMS capacitive switches with the proposed beam within the range of 1uN to 3uN. Using ANSYS software, we have also compared relevant parameters of these structures such as actuation voltage, resonant frequency, collapse voltage, displacement sensitivity and spring constant.

Fixed-Fixed beams are usually more favorite because of high reliability and also easy manufacturing. We therefore preferred fixed-fixed structure for analysis and simulation.

Among advantages associated with the proposed structure over the conventional ones, we should mention low actuation voltage and smaller size, which results in longer life for battery and also easier packaging, hence lower manufacturing costs.

As pointed out already, the main drawback with the proposed beam compared to the other structures is high undesirable stress. By improvement through the arc-like curves this stress is relaxed to some extent.

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