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Pull-in Voltage Study of Various Structured Cantilever and Fixed-Fixed Beam Models using COMSOL Multiphysics

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Abstract

The present work involves the study of pull-in voltage of MEMS electrostatic Cantilever beam, Fixed-Fixed beam and modified beam structures with perforations of square, rectangular and circular shapes. The analysis is done using COMSOL 4.3 software. The dimensions of the Cantilever beam, Fixed-Fixed beam and three various structured beams modeled in this paper are length = 300 µm, width = 50 µm, thickness = 3 µm and gap between top electrode and ground plane is 2.5 µm. The pull-in voltage obtained for Cantilever beam is 17.6 V and for Fixed-Fixed beam is 118.8 V. For the modified models with square, rectangular and circular perforations are 12.18 V, 15.45 V and 13.75 V respectively. The results of the work demonstrate an ability to achieve lower pull-in voltage levels for three various structured beams modeled in this paper when compared to cantilever and Fixed-fixed beams. The dependence of the pull-in voltage on geometrical parameters, thrusts on stringent design considerations even at the initial stages.

Keywords: Cantilever, COMSOL, Deflection, Fixed-Fixed, Perforated beams, Pull-in Voltage

1. Introduction

Electrostatic actuation is a popular methodology adopted in MEMS technology for realizing actuators because of good scaling properties with scaling. It has good sensitivity and energy densities. Realization of new design concepts and low-power consumption is also possible. These types of transducers are consists of deformable diaphragm, cantilever beam which is fixed at both ends known as the fixed-fixed beams[1]. This is separated from a fixed ground plane by an air gap of suitable thickness. In these devices, the drive mechanism consists of a constant voltage source (voltage drive) or constant current source (current drive) for enabling electrostatic actuation. The widely used capacitive type sensors and actuators are Micro fabricated cantilever and Fixed-Fixed beams. The drive mechanism used in most of these devices is constant voltage source. In constant voltage source or voltage drive the electrostatic force or bias voltage used is non-linear and leads to the phenomenon of 'pull-in'. Young's modulus and the residual stress of micro fabricated thin films can be determined using pull-in voltage[2].

Pull-in voltage determination in parallel-plate approximation method incorporates a piston like motion of the beam under the assumption of a linear spring constant. This method predicts the occurrence of pull-in when the highest deformation of the movable structure exceeds one-third of the air gap. This paper involves the study of the pull-in voltage of MEMS electrostatic Cantilever, Fixed-Fixed beam type and it is compared with pull-in voltage of three various structured beams. Numerical simulations were validated by simulating pull-in volt-

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age with that of the experimental results[3].The results of the work demonstrate an ability to achieve lower pull-in voltage levels for three various structured beams modeled in this paper when compared to cantilever and Fixed-fixed beams. Impact of any combination of these three structured beams on pull-in voltage is helpful for design decision making on the early stages of this type of structures. This cantilever and Fixed-Fixed beams with appropriate modification can be made as a switch, wherein electrodes and contact pads can be added.

2. Geometrical Modeling of Beams

The cantilever of Length (L), Width (W) and of Thickness (H) is modeled as shown in Figure 1. The electric potential (V) is applied across the top surface of the beam and ground as indicated in the Figure 1. The gap between the beam and ground electrode is assumed to be air with a thickness of 'g_0'

The Top view of beam is as shown in Figure 2. For Cantilever, one end of beam is fixed and other end is free as shown in Figure 1, but for Fixed-Fixed beam, both ends of beam are fixed. The Cantilever beam and three other various structured Cantilever beams are modeled in this paper. The Dimensions of beam are Length = 300 μm, Width = 50 μm, Thickness = 3 μm, and Gap between ground electrode and beam is 2.5 μm. The three other various structured beams consist rectangular, square, and circular shaped etch holes of proper dimensions on beam surface.

The Top view of beam structure with rectangular etch holes on beam surface is shown in Figure 3. The rectangular etch holes on beam surface dimensions are Length = 40 μm, Width = 15 μm, Thickness = 3 μm. These rectangular shaped etch holes pattern on beam are as shown in Figure 3.

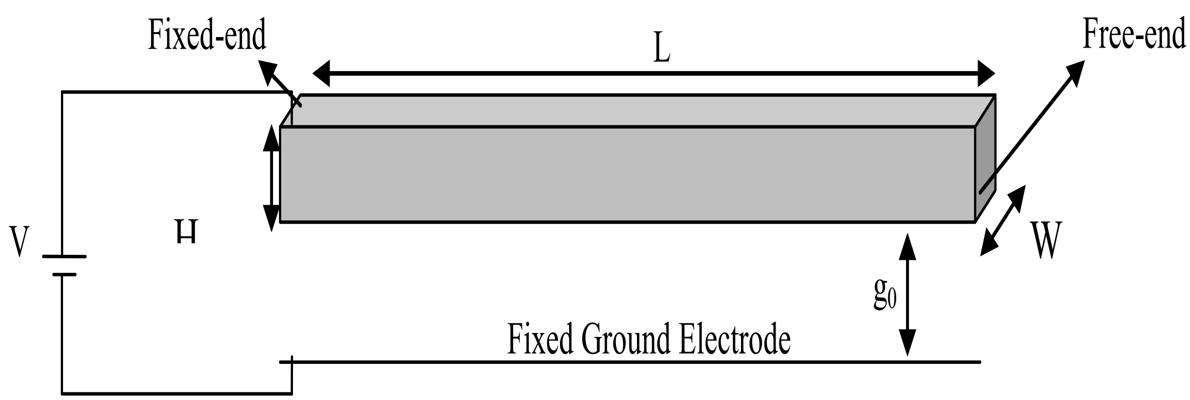

Figure 1. Geometric model of Cantilever beam.

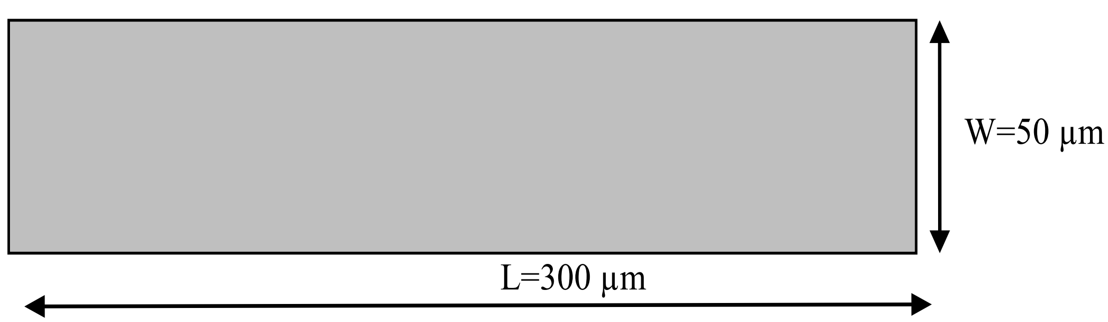

Figure 2. Top View of Beam cantilever beam.

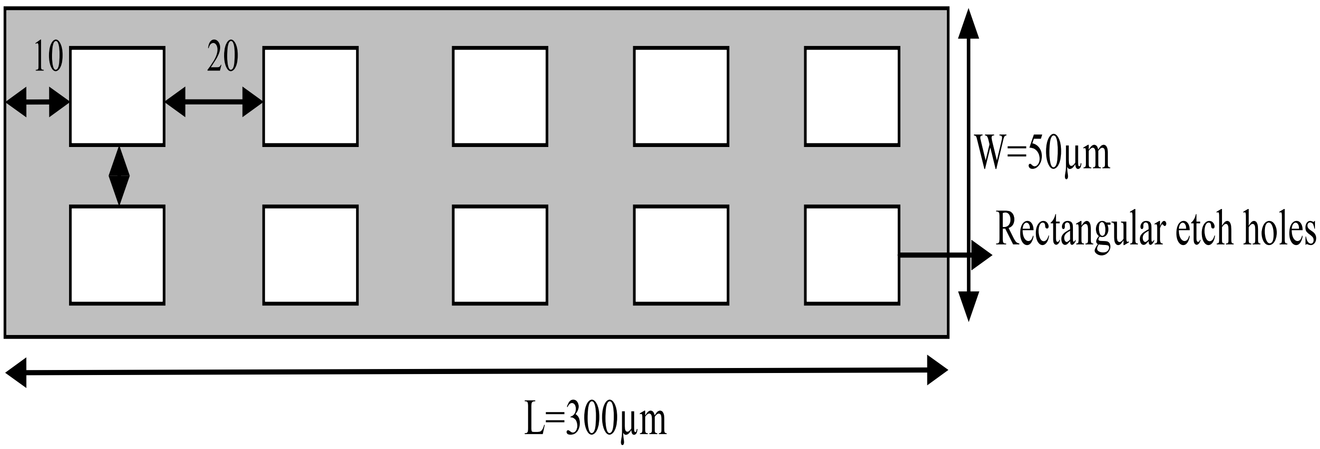

Figure 3. Top view of beam with rectangular etch holes of dimensions 40 µm x 15 µm.

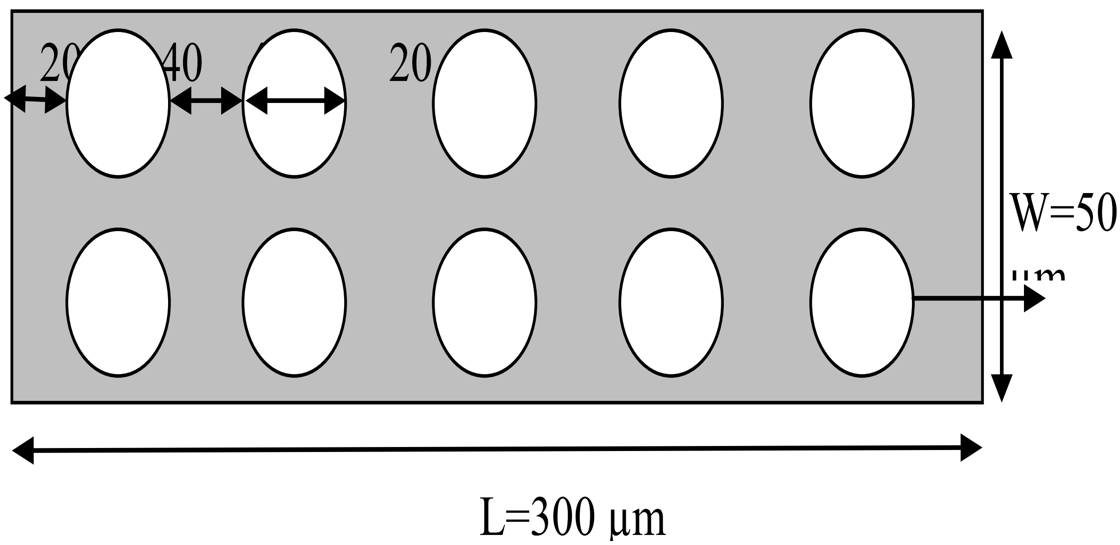

Figure 4. Top view of beam structure with circular etch holes of radius =10 µm.

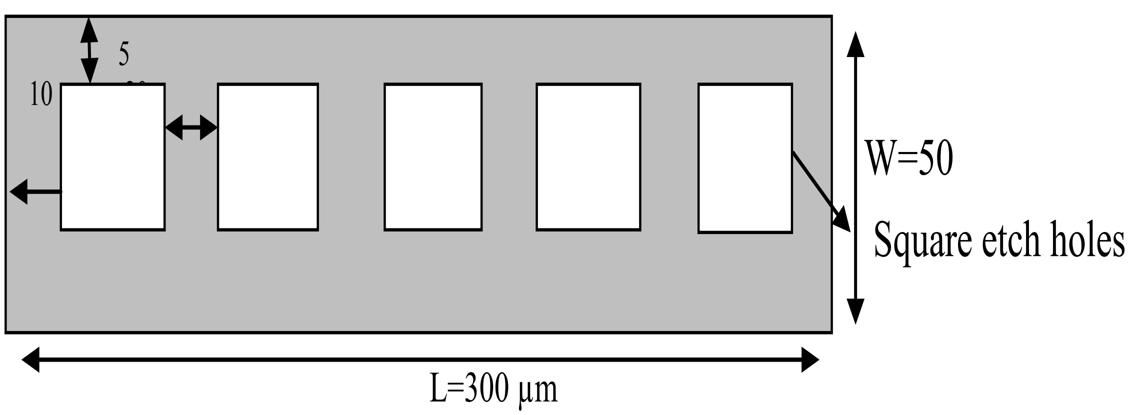

Figure 5. Top view of beam structure with square etch holes of dimensions 40 µm x 40 µm.

The Top view of beam structure with circular etch holes on beam surface is shown in Figure 4. The circular etch holes on beam surface dimensions are radius = 10 µm, thickness = 3 µm. These circular etch holes pattern on beam are as shown in Figure 4. The Top view of beam structure with square etch holes on beam surface is shown in Figure 5. The square etch holes on beam surface dimensions are length = 40 µm, width = 40 µm, thickness = 3 µm. These square etch holes pattern on beam are as shown in Figure 5.

3. Pull-in Voltage Analysis for Cantilever and Fixed-Fixed Beam

Figure 6 shows basic electrostatic actuator. When a potential is applied across the parallel plates of a capacitor, there will be electrostatic force acting on between plates to bring them closer and minimize the electrical potential energy of the system. By increasing voltage, gap decreases. At some critical voltage, system goes unstable, gap collapses to zero. This phenomenon is called Pull-In. By increasing voltage, equilibrium gap decreases, there will be specific voltage at which stability of equilibrium is lost. This voltage is called Pull-in voltage ($V_{Pull-in}$).

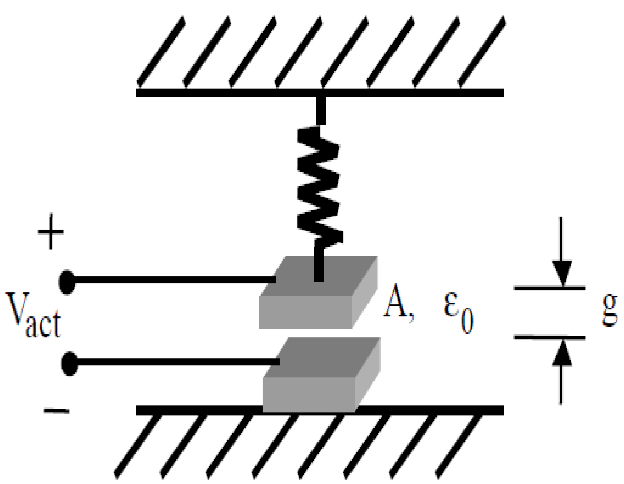

Figure 6. Basic Electrostatic Actuator.

Silicon is selected as material for the top electrode. The material properties of the silicon accounted are young's modulus (E=169 GPa). The analytical expression used to calculate pull-in voltage of Cantilever beam is given by equation

$$V_{Pull-in} = \sqrt{\frac{4c_1 B}{\varepsilon_o L^4 c_2^2 \left(1 + c_3 \dfrac{g_o}{W}\right)}} \tag{1}$$

where $B = \hat{E} H^3 g_o^3$

Where normalised constatnts C1 = 0.07, C2 = 1.00, C3 = 0.42, go = Initial gap between the beam and ground (2.5 µm), L = Length of beam (300 µm), W = Width of beam (50 µm), H = Thickness of beam (3 µm), Ê = Young's modulus of silicon(169 GPa), ε_0 = Permittivity of free space (8.85 x 10^{-12} F/m). The analytical equation used to calculate pull-in voltage of Fixed-Fixed beam is given by equation[1].

4. Numerical Methodology

The COMSOL simulations of pull-in voltage analysis for Cantilever beam, and three other structured beams modeled in this paper are as follows. The Boundary Conditions (BC) for various structures are voltage BC and fixed BCs.

4.1 Cantilever Beam Simulations

COMSOL Simulations of Cantilever beam with rectangular, circular, square shaped etch holes are shown in Figure 7, Figure 8, Figure 9 and Figure 10 respectively. For all the structures air block dimensions that surrounding the beam are 300 µm x 50 µm x 6 µm.

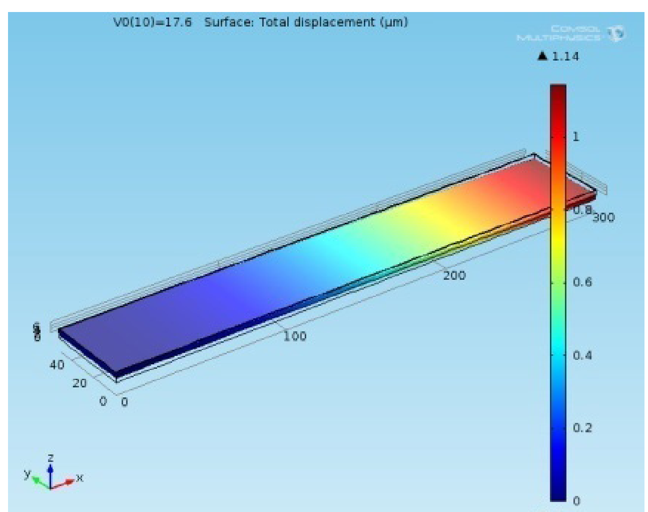

Figure 7. Micro cantilever showing deflection due to applied voltage.

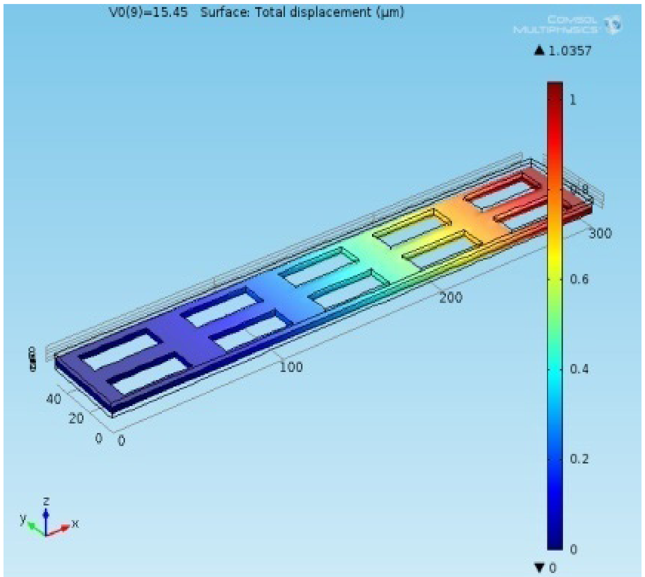

Figure 8. Rectangular shaped etch holes structured Micro cantilever showing deflection due to applied voltage.

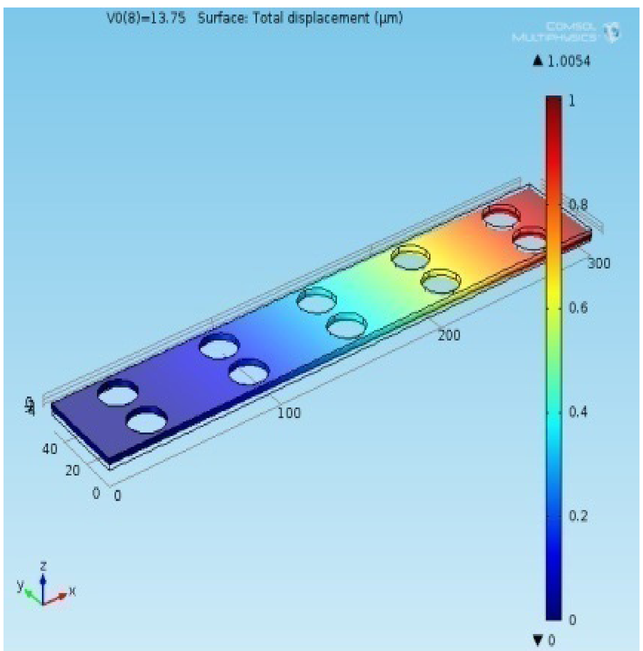

Figure 9. Circular shaped etch holes structured Micro cantilever showing deflection due to applied voltage.

4.2 Fixed-fixed Beam Simulations

The numerical simulations of pull-in voltage analysis for Fixed-Fixed beam and three other beam structures mod-

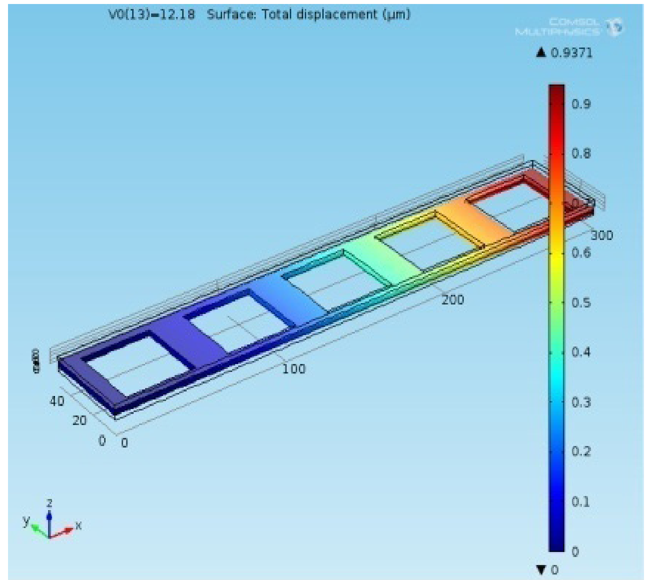

Figure 10. Square shaped etch holes structured Micro cantilever showing deflection due to applied voltage.

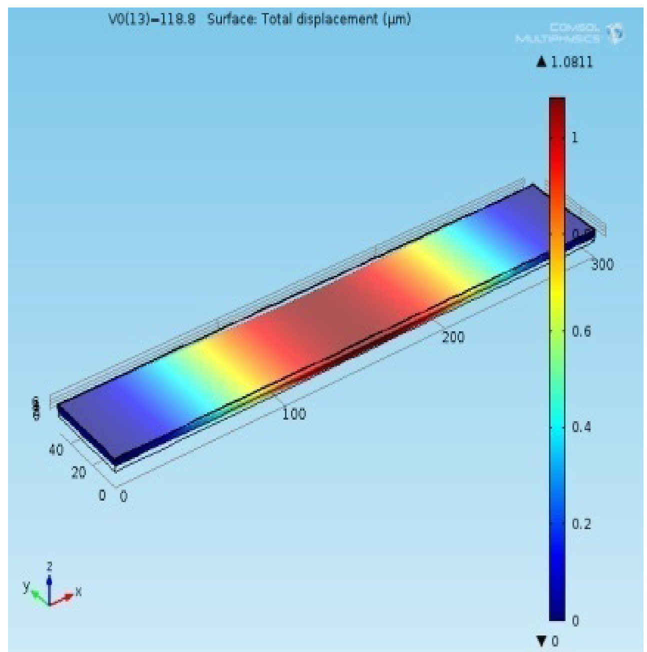

Figure 11. Fixed-Fixed beam showing deflection due to applied voltage.

eled in this paper are as follows. Fixed-Fixed beam and fixed-fixed beams with rectangular, circular and square shaped etch holes are shown in Figure 11-14 respectively.

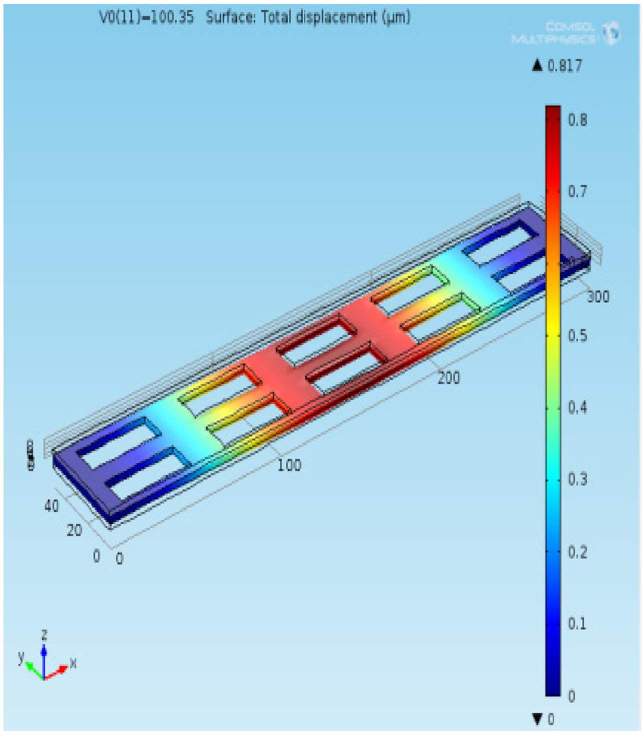

Figure 12. Rectangular shaped etch holes structured Fixed-Fixed beam showing deflection due to applied voltage.

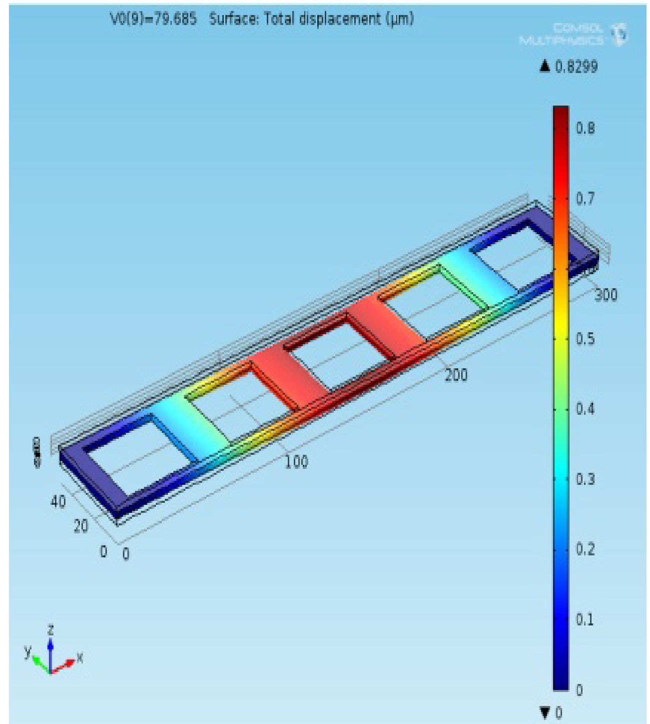

Figure 14. Square shaped etch holes structured Fixed-Fixed beam showing deflection due to applied voltage.

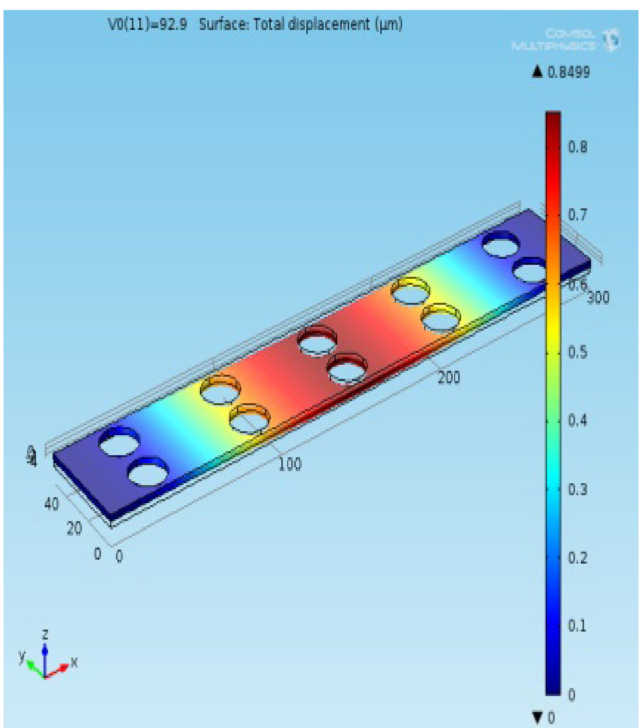

Figure 13. Circular shaped etch holes structured Fixed-Fixed beam showing deflection due to applied voltage.

5. Results and Discussion

The Analytical value of Pull-in voltage for Cantilever and Fixed-Fixed beam is calculated by using equation (1) and formulae mentioned in reference1. The Cantilever has Pull-in Voltage of 16.51 V and for Fixed-Fixed beam has Pull-in Voltage of 114.03 V. The numerical results for Pull-in Voltages of 17.6 Volts for cantilever beam and 118.8 Volts for Fixed-Fixed beam were obtained. The analytical results are close to numerical results and listed in Table 1 with all dimensions and Plotted as graph shown in Figure 15. So the calculated pull-in voltage has been validated by experimental and theoretical results and a good agreement has been achieved. The Pull-in Analysis of various shaped beams also simulated using COMSOL and also has been compared with simulations of Cantilever and Fixed-Fixed beam. The Table 2 illustrates Pull-in Voltage comparison For Cantilever and its three other shapes with clearly mentioned dimensions and plotted as graph shown in Figure 16. The Table 3 illustrates Pull-in Voltage comparison For Fixed-Fixed beam and its three other shapes with clearly mentioned dimensions and plotted as graph shown in Figure 17.

Table 1. Comparison of Pull-in Voltages for Cantilever and Fixed-Fixed beam

	Analytical Pull-in voltage (V)	Numerical Pull-in voltage (V)
Cantilever beam	16.51	17.6
Fixed-Fixed beam	114.03	118.8

Table 2. Comparison of Pull-in Voltages for Cantilever beam and Rectangular, Circular, Square shaped etch holes structured Cantilevers

Cantilever beam	$V_{Pull\text{-}in}$	% Reduction of $V_{Pull\text{-}in}$
Without perforations	17.60	-
With rectangular shaped etch holes	15.45	12.21 %
With circular shaped etch holes	13.75	21.80 %
With square shaped etch holes	12.18	30.79 %

Table 3. Comparison of Pull-in voltages for Fixed-Fixed beam and Rectangular, Circular, Square shaped etch holes structured Fixed-Fixed beams

Fixed-fixed beam	$V_{Pull\text{-}in}$	% Reduction of $V_{Pull\text{-}in}$
Without perforations	118.8	-
With rectangular shaped etch holes	100.35	15.53 %
With circular shaped etch holes	92.9	21.80 %
With square shaped etch holes	79.685	32.92 %

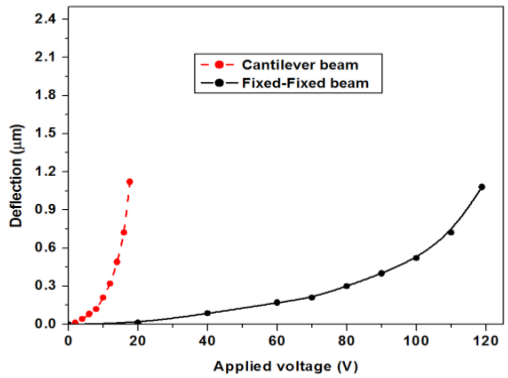

Figure 15. Variation of maximum deflection with applied voltage until Pull-in for cantilever and Fixed-fixed beam.

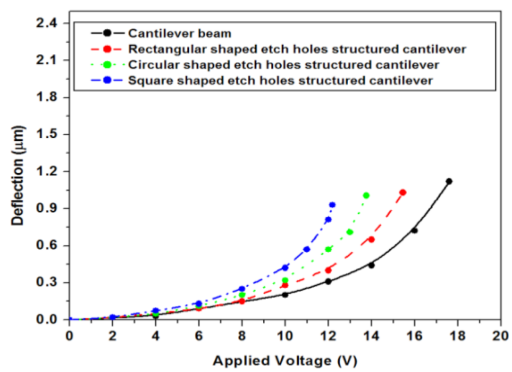

Figure 16. Variation of maximum deflection with applied voltage until Pull-in for cantilever and rectangular, circular, square shaped modified cantilevers.

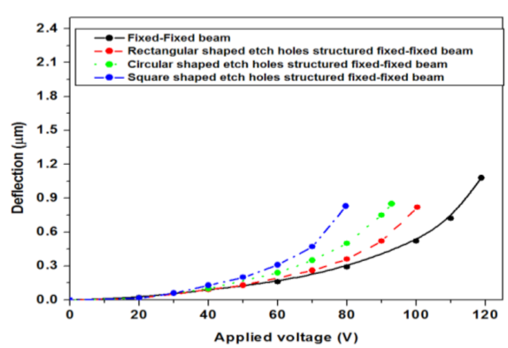

Figure 17. Variation of maximum deflection with applied voltage until Pull-in for Fixed-Fixed beam and rectangular, circular, square shaped modified Fixed-Fixed beams.

6. Conclusion

When compared to Cantilever beam and Fixed-Fixed beam, the other three structures mentioned in this paper with etch holes on beam surface resulted in lower Pull-in voltage values. From COMSOL Simulations Square shaped etch holes structured cantilever beam and square shaped etch holes structured Fixed-Fixed beam models has lowest pull-in voltage levels. The reason for this kind of behavior is lessened membrane stiffness also because of reduced squeezed film damping. After reaching the pull-in Voltage levels the gap between beam and ground electrode reduced and collapses to zero thus it forms closed contact and used as a switch. From results it is observed that pull-in voltage state is achieved at more than one-third of initial gap between beam and ground plane i.e. (g_0 = 2.5 µm). So the pull-in voltages are achieving when gap between beam and ground plane is in range of 0.8 µm – 1.2 µm. Impact of any combination of these three structured beams on pull-in voltage is helpful for design decision making on the early stages of this type of structures. This paper concludes that instead of using simple Cantilever and Fixed-Fixed beams for pull-in voltage analysis, beam with square shaped perforations yielded lower values of pull-in voltages.

7. References

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