Journal of Nano- and Electronic Physics
Vol. **16** No 6, 06018(5pp) (2024)

Журнал нано- та електронної фізики
Том **16** № 6, 06018(5сс) (2024)

REGULAR ARTICLE

Simulation Study and Reliability Analysis of Low Actuation Voltage Cantilever Based RF MEMS Switch

Shivashankar A. Huddar[1,*], B.G. Sheeparmatti[2], A.Y. Patil[3,†], Nalini C. Iyer[1], Raman Kumar[4], Shridhar N. Mathad[5]

[1] *School of Electronics and Communication Engineering, KLE Technological University, BVB Campus, 580031 Hubballi, India*
[2] *Department of Electronics and Communication Engineering, Basaveshwar Engineering College, 587102 Bagalkot, India*
[3] *Department of Mechanical Engineering, Manipal Institute of Technology Bengaluru, Manipal Academy of Higher Education, Manipal, 576104 Karnataka, India*
[4] *University Centre for Research and Development, Department of Mechanical Engineering, Chandigard University, Mohali, Punjab, India*
[5] *Department of Engineering Physics, K.L.E. Institute of Technology, Gokul Road, Hubballi, 580027 Karnataka, India*

(Received 10 August 2024; revised manuscript received 19 December 2024; published online 23 December 2024)

This paper reemphasizes the importance of material consideration to design a low pull-in voltage MEMS switch. We have simulated different variants of a cantilever-based MEMS switch with variations in length, thickness, and material of the cantilever beam. The simulation study provides an understanding of a suitable cantilever design to achieve low operating voltage MEMS switch. We have further simulated the mechanical properties of these designs of the cantilever beam for a low operating voltage by computing the equivalent electrostatic force which is the input to the mechanical simulations performed using ANSYS. The electromechanical simulation provided similar trends of deflection and validates some aspects of the cantilever beam design especially for the material choice that can aid to achieve a low actuation voltage. The paper also provides a better understanding of the deflection variations that can be seen with change in material; when a switch is actuated, the deflections for actuation hover around 2/3rds of the gap in a cantilever-based RF MEMS switch with a standard deviation of 0.3 μm. The key contributions of the paper is: 1) showing that the cantilever beam design is critical for achieving low actuation voltage, 2) deflections of the cantilever at actuation voltage depends on the material used and can be around 2/3rds of the gap and can be slightly less for some materials, and, 3) a comparative simulation study between electrostatic and mechanical simulations to provide information on structural integrity of the simulated cantilever beams for MEMS switch.

Keywords: MEMS, Simulation, Cantilever.

DOI: 10.21272/jnep.16(6).06018 PACS numbers: 85.85. + j. 87.15.Aa, 68.35.Gy

1. INTRODUCTION

Micro-Electro-Mechanical-System (MEMS) comprising of Electronics and mechanical components in a single model [1]. The conventional CMOS switches are less favorable as they suffer from off-state capacitances, low isolation, and high insertion loss over the Radio-Frequency (GHz) range [2]. Today, Radiofrequency micro switches can replace the existing conventional switches because of their feasibility and compatibility in the working domain. RF MEMS have low pull-in voltage and insertion loss, as far as its peers [1-4]. Electrostatic, piezoelectric, Magnetostatic, and thermal actuation are the possible configurations in MEMS-based switches [1]. There are different configurations of RF MEMS switches among these considering type of contact; these switches are classified as series and shunt switches. A series switch uses metal-to-metal contact to address problems relevant to one end and two ends fixed beam [5]. In off mode conditions, the series switch acts as an electrically open circuit, however, in the mode of RF power flow in a transmission line [1]. Shunt capacitive switches use a two-end fixed structure, wherein input RF power is equal to the output RF power upstate. Output RF power is equal to zero in the downstate [6]. The Radio frequency Micro Electro Mechanical Switches' performance is due to dynamic behavior of mechanical components lead to early failure of the device [10, 11]. Stiction issue can be overcome by increasing the beam restoring force by keeping the operating voltage less than 60V. Perhaps, to reduce the stiction a coating of siloxane is preferred [12, 13]. The authors' exhaustive literature survey has yielded a relative difference between experimental/analytical/simulation results, especially for pull-in voltage is 0.7 to 10 % and pull-in deflection is 1.1

* Correspondence e-mail: shivashankar.a.huddar@gmail.com
† physicssiddu@kleit.ac.in

to 18 % [14, 15]. This paper mainly focused on the Pull-in voltage for various cantilever structures.

Till date researchers have focused on mainly two ways of designing RF MEMS such as both end fixed condition or cantilever beam method. Among these a cantilever beam is preferred for low pull in voltage. Cantilever beam reaches a position that corresponds to 2/3 of the original gap between the microbeam and the actuator electrode, that point is called Pull-in voltage [16]. Electro static actuation is considered in the proposed work. The micro-cantilever beam consisting of material properties such as Young's modulus, Density, and Poisson's ratio, as illustrated in Table 1. Whenever voltage is applied to the actuator electrode, electrostatic force exists between the cantilever beam and actuator electrode, because of which the beam starts bending towards the transmission electrodes.

Table 1 – Different materials to design MEMS Switch and their properties

Materials	Young's Modulus (GPa)	Poisson's ratio	Density (kg/μm³)
Copper	120	0.34	8.96×10^{-3}
Titanium	110	0.333	4.50×10^{-15}
SMA	83	0.33	6.45×10^{3}
Aluminium	77	0.3	2.30×10^{-15}
Gold	57	0.35	1.93×10^{-14}

The MEMS Switch consists of a micro cantilever beam made up of metal suspended on the actuator electrode and transmission electrodes. Actuating electrode fixed at one end and the other end free to move. A schematic of the switch, as shown in Figure 1. The 275 μm thick-layer silicon substrate material is used as the base material to build a micro switching device – the cantilever beam designed with suspended 2 μm above the actuator electrode. The potential difference is created between the micro cantilever beam and the actuator electrode by applying voltage. The cantilever beam starts bending towards the substrate. When the beam begins moving towards the actuator electrode, the stand of distance between the beam and actuator reduces. When the operating voltage is applied to beam, it gets connected with transmission electrodes. The cantilever beam dimensions of length 296 μm, width 14 μm, and thickness 0.5 μm shown in Figure 1 [16, 17]. From Figure 1 it can be inferred that, a top view of actuator electrode and transmission electrodes are considered for transmission of signal.

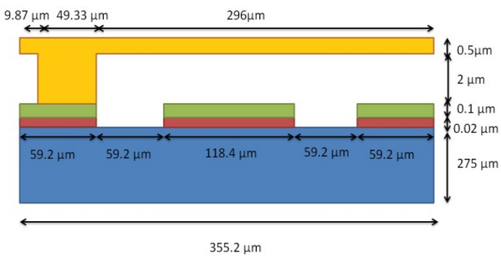

Fig. 1 – Side view of switch with beam length 296 μm and 0.5 μm thick

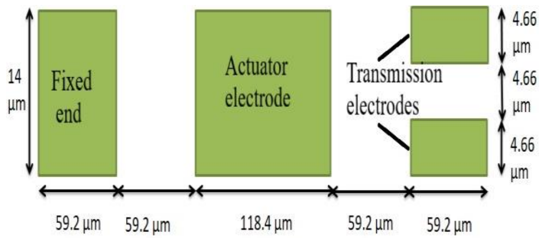

Fig. 2 – Top view of actuator electrode and transmission electrodes

The actuation voltage of the switch calculated by using the formula shown below [3]:

$$V_{PI} = \sqrt{\frac{8Kd^3}{27A\epsilon_0}} \qquad \text{(i)}$$

$$K = \frac{EWt^3}{12L^3} \qquad \text{(ii)}$$

Where,

t is the thickness of the cantilever beam.

K is spring constant.

d is a gap between cantilever beam and actuator electrode. E is Young's modulus, L is the beam length. $A = w \times W$. where w is the beam's width, and W is the actuator electrode, ϵ_0 is the permittivity of free space (8.854×10^{-12}) farads/meter.

2. SIMULATION WITH ANSYS WORKBENCH

Today simulation has come to the forefront, especially after the Industry Internet of Things (IIOT) [18]. However, Micro Electro Mechanical Systems (MEMS) have come a long way in simulation studies. To date, it's quite challenging to work on the experimental aspects of MEMS as the sophisticated facility is missing in many laboratories around the world. This has made a simulation to gain high importance in MEMS and NEMS industries.

2.1 Geometry

The MEMS model was built in design modeler of ANSYS 18.2 and subjected to simulation, as shown in Figure 3.

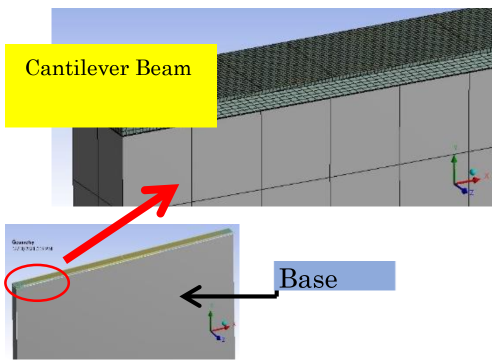

Fig. 3 – Setup of Micro Electro Mechanical Switch

2.2 Contact Generation

The model is considered a 'Bonded' contact between the various layers [19]. The bonded joint resembles a permanent joint with equivalent to welding in mechanical terminology. The details of contact generated with the 'Pure penalty' approach for an 'Asymmetric' condition, as shown in Figure 4.

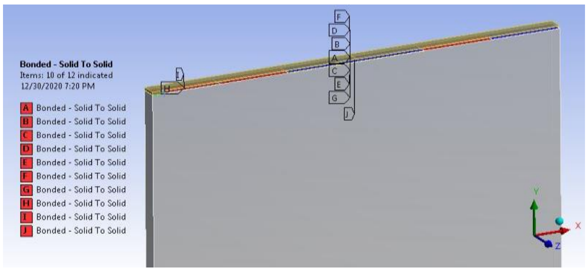

Fig. 4 – Contact generation of Micro Electro Mechanical Switch

2.3 Mesh Generation

The entire model is assigned with *H*-Type and *P*-Type based mesh generation. The element type is Hexa-dominant with mid-side node kept resulted in 20 nodes. Solid 186 considered from the library of ANSYS, as shown in Figure 5.

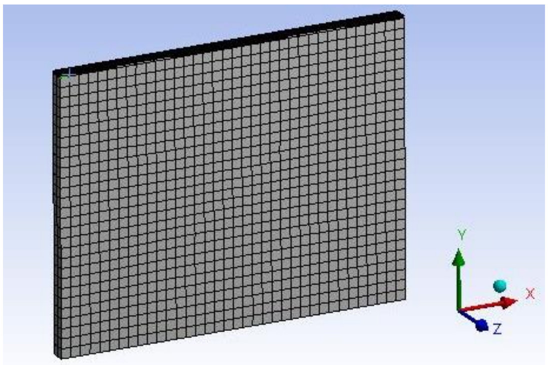

Fig. 5 – MESH generation of micro electro mechanical switch

The statistics for the current model noted 303544 nodes and 53092 elements.

2.4 Loads and Boundary Conditions

The bottom surface is constrained with all six degrees of freedom and a force of 2.5×10^{-3} μN, as shown in Figure 6.

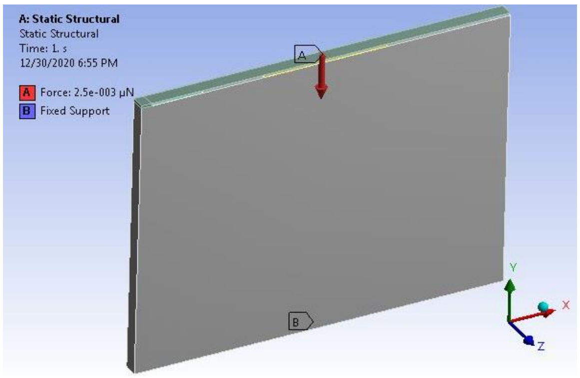

Fig. 6 – Loads and Boundary conditions

3. RESULT AND DISCUSSIONS

3.1 Pull-in voltage for different materials

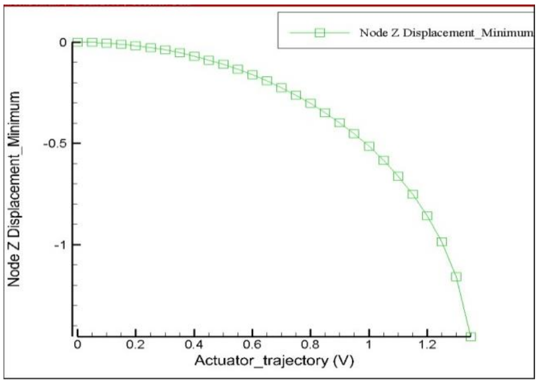

Fig. 7 – Pull-in voltage v/s Displacement of switch with beam length 296 μm and 0.5 μm thick GOLD

This section includes a discussion of pull-in voltage for different materials like Nickel, Silicon, Copper, Titanium, SMA, Aluminium, Gold for all the above-discussed designs, and plots of pull-in voltage v/s displacement is shown in Table 2 and 3.

Observing the Table 1-2 and Figure 7, it is concluded that lesser pull-in voltage can be achieved using gold as beam material. Lowest pull in voltage of 1.35 volts is observed for the switch where the beam length is 296 μm, width is 14 μm and thickness 0.5 μm.

3.2 Total Deformation

The total deformation observed on the model is 1.219 μm, as shown in Figure 8, which is equivalent to less than 1/3rd deformation value for the base(Y-direction downward). As it comes to be 1.3 μm, it is still within the acceptable limits.

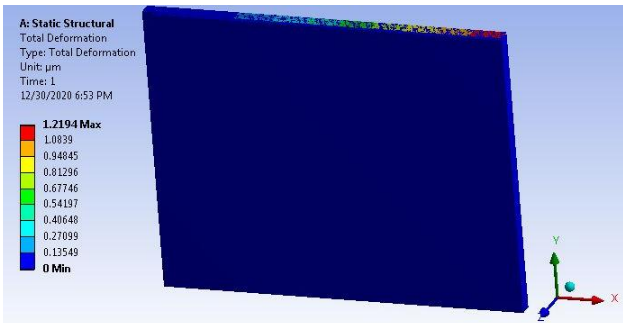

Fig. 8 – Total deformation

3.3 Von Mises Stress

The reported stress value is 0.766 MPa for a given load condition. The observed value is well within the yield or ultimate strength criteria of the material assigned [20].

3.4 Modal Analysis

The forced vibration extracted for 12 modes. The results extracted for forced vibration shown a range of frequency values from 2.9 Hz to 61 Hz. The fundamental frequency is highlighted.

3.5 Fatigue Analysis

Fatigue analysis is the critical simulation module in structural design. Fatigue analysis is carried out to realize the number of cycles a system can survive for a typical load conditions. As modern technologies have predominant usage of electronics component such as sensors, actuators to name few and these will be subjected to continuous usage. To check the reliability and durability of the system fatigue analysis has gained lot of importance. To calibrate the tool or system life based on number of cycles, factor of safety, damage and bi-axiality indication fatigue module is quite useful [23].

Table 2 – Pull-in voltage of switch with beam length 296 μm, width 14 μm and 1 μm thick

Materials	Pull-in voltage (in volt)	Displacement (in μm)
Copper	5.5	– 1.45
Titanium	5.25	– 1.416
SMA	4.5	– 1.29
Aluminium	4.25	– 1.172
Gold	3.75	– 1.32

Table 3 – Pull-in voltage of switch with beam length 296 μm, width 14 μm and 0.5 μm thick

Materials	Pull-in voltage (in volt)	Displacement (in μm)
Copper	1.95	– 1.4
Titanium	1.85	– 1.32
SMA	1.6	– 1.28
Aluminium	1.55	– 1.343
Gold	1.35	– 1.454

We need to infers the details about input parameters required to solve the given system for fatigue analysis. The problem of MEMS for cantilever beam analyzed for stress based approach with mean stress theory considered is modified Goodman [20]. The entire loading pattern is as a sinusoidal form.

The results for 0.25 μN load acting at midspan of cantilever beam showed 76.655 MPa of alternating stress. However, the commercially acceptable range for RF MEMS switch is upto to 100 billion cycles at 100 mW RF input power [23, 24].Which is considered to be safe design for 1.77×10^{8} cycles as illustrated in Figure 9a. The minimum number of cycle required for serving the intended purpose for end user is 1 lakhcycles. From Figure 9c it can be understood, that damage behavior is well above unit scale factor, resembling a safe design in terms of tolerance. The system considered very critical if it falls below 1 scale factor [20]. Factor of safety (FOS) is another critical parameter which influences the fatigue life of a system. For any mechanical or structurally rigid member the nominal FOS needs to be in the range of 1.1 to 1.5. For micro and nano based components it is acceptable in the range of 1-1.3 whereas Figure 9d shows 0.613 still this can be considered based on the number of cycles. The reliability and durability aspects based on these parameters it is well within the threshold limit or as per design criteria. The simulation study carried out in ANSYS is compared with simulink results for validation based on the earlier work [20].

4. CONCLUSIONS

An exhaustive work on simulation and analytical calculation is done. The pull-in voltage readings were tabulated and discussed for different materials such as Nickel, Silicon, Copper, Titanium, SMA, Aluminum, and Gold for micro-cantilever beam of dimension. The optimal design is obtained for switch with beam length 296 μm, width 14 μm and thickness 0.5 μm. In ANSYS workbench, the simulation results showcase a compatibility with analytical and CoventorWare FEA. The error percentage for pull-in deflection observed is less than 24 % for gold micro cantilever, whereas pull-in voltage is less than 5 %. Which is within acceptable range as per the norms of industry.Fundamental frequency of a cantilever beam reported in a range of 2.9 MHz to 61 MHz for a forced vibration. For constant force value of 2.5×10^{-3} μN is subjected to harmonic analysis.

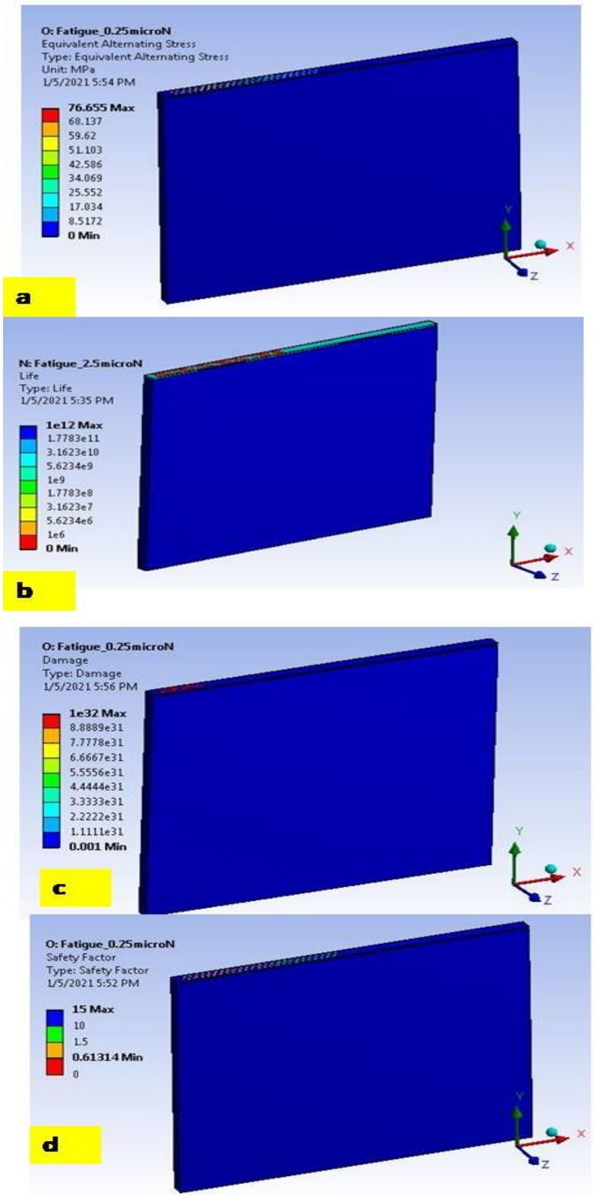

Fig. 9 – a) Input parameters details of fatigue tool b) Fatigue life c) Damage tolerance d) Factor of safety

Higher the frequency conducive for system and lower the frequency detrimental to the system. Fatigue analysis solved for damage, factor of safety and extraction for number of cycles (1.77×10^8 cycle's equivalent to 100 billion cycles) observed to be well within the threshold limit of the design criteria. Hence it can be concluded that gold is the best-suited material for microcantilever beam, and it is also observed that pull-in voltage reduces if the thickness of the beam reduces and length increases.

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Моделювання та аналіз надійності радіочастотного MEMS-перемикача з низькою напругою спрацьовування

Shivashankar A. Huddar[1], B.G. Sheeparmatti[2], A.Y. Patil[3], Nalini C. Iyer[1], Raman Kumar[4], Shridhar N. Mathad[5]

[1] *School of Electronics and Communication Engineering, KLE Technological University, BVB Campus, 580031 Hubballi, India*

[2] *Department of Electronics and Communication Engineering, Basaveshwar Engineering College, 587102 Bagalkot, India*

[3] *Department of Mechanical Engineering, Manipal Institute of Technology Bengaluru, Manipal Academy of Higher Education, Manipal, 576104 Karnataka, India*

[4] *University Centre for Research and Development, Department of Mechanical Engineering, Chandigard University, Mohali, Punjab, India*

[5] *Department of Engineering Physics, K.L.E. Institute of Technology, Gokul Road, Hubballi, 580027 Karnataka, India*

Стаття присвячена вивченню матеріалів для розробки MEMS-перемикача з низькою напругою. Було змодельовано різні варіанти консольного MEMS-перемикача з різними довжиною, товщиною та матеріалом консольної балки. Моделювання дає розуміння відповідної конструкції кантилевера для досягнення низької робочої напруги перемикача MEMS. Було додатково змодельовано механічні властивості цих конструкцій консольної балки для низької робочої напруги шляхом обчислення еквівалентної електростатичної сили, яка є вхідними даними для механічного моделювання, виконаного за допомогою програмного забезпечення ANSYS. Електромеханічне моделювання показало подібні відхилення значень та підтвердило деякі аспекти конструкції консольної балки, особливо для вибору матеріалу, який може допомогти досягти низької напруги спрацьовування. Коли перемикач спрацьовує, відхилення для спрацьовування коливаються навколо 2/3 зазору в RF MEMS-перемикачі на основі консольного важеля зі стандартним відхиленням 0,3 мкм. Показано, що конструкція консольної балки має вирішальне значення для досягнення низької напруги спрацьовування. Відхилення консолі при напрузі спрацьовування залежить від використовуваного матеріалу та може становити приблизно 2/3 зазору та може бути трохи меншим для деяких матеріалів. Проведені порівняльні моделювання електростатичного та механічного моделювань для отримання інформації про структурну цілісність консольних балок для перемикача MEMS.

Ключові слова: MEMS, Моделювання, Кантелівер.