International Journal of Reconfigurable and Embedded Systems (IJRES)
Vol. 11, No. 2, July 2022, pp. 146~156
ISSN: 2089-4864, DOI: 10.11591/ijres.v11.i2.pp146-156

Features measurement analysis of pull-in voltage for embedded MEMS

Hajar Baghdadi[1,2], Mohamed Lamhamdi[1], Karim Rhofir[2]
[1]RMI Laboratory, Faculty of Science and Technology, Hassan 1st University, Settat, Morocco
[2]LaSTI Laboratory, National School of Applied Sciences, Sultan Moulay Slimane University, Beni Mellal, Morocco

Article Info

Article history:

Received Dec 28, 2021
Revised Jan 22, 2022
Accepted Feb 21, 2022

Keywords:

Analysis
Embedded MEMS
Internet of things
Modeling
Pull-in

ABSTRACT

The embedded micro electro mechanical systems (MEMS) is a technology that is creating a new era in all fields and especially in the internet of things (IoT) field. MEMS are necessary components for the realization of tiny micro/nano circuits. For this reason, designers are facing many challenges in designing embedded MEMS for achieving efficient products. The pull-in voltage is one of the most important parameters of MEMS design. In this work, we are interested in the analysis of some geometrical and mechanical parameters for the pull-in. The objective is to study of the concept of pull-in voltage in order to reduce it. First, we made a simulation to choose the appropriate material achieving a lower pull-in voltage. Then, we analysed the impact of geometrical parameters on the pull-in voltage. In this work, Finite element method using COMSOL Multiphysics® software is employed to compute the Pull-in voltage and study the behaviour of the MEMS Switch in order to optimize it. Pull-in voltage can be reduced by careful selection of the cantilever material and it can be further reduced by changing the beam parameters.

Corresponding Author:

Hajar Baghdadi
RMI Laboratory, Faculty of Science and Technology, Hassan 1st University
Settat, Morocco
Email: h.baghdadi@uhp.ac.ma

1. INTRODUCTION

Embedded micro-electro mechanical systems have become a daily necessity. Through the years, these manufactured devices have decreased in size and increased in efficiency. Micro electro mechanical systems (MEMS) technology has generated a significant amount of interest in the government and business sectors [1]. This interest is happening due to the potential performance and cost advantages with micro-scale devices embedded in a portable system and can be manufactured at low cost. As we know, the term MEMS is the combination of two different systems that is mechanical and electrical systems such as MEMS actuators and MEMS sensors including MEMS switches and MEMS accelerometers [2]–[4]. Furthermore, MEMS switches embed the advantages of mechanical and semiconductor properties in a small size. This property of the MEMS switch can be applied to radio frequencies (RF), hence the name RF-MEMS switch [5]. For example, RF-MEMS filters and resonators are intended for applications such as duplex filters, RX&TX band filters, global positioning system (GPS) filters, VCOs, reconfigurable antennas and reference oscillators [6]–[8]. The other application field is RF-MEMS switches, which are very interesting for multi-system phones and with IoT [9], [10].

Electrostatically actuated MEMS switches can operate in an extremely power saving mode, they do not generate distortion of the signal. These categories are important in the present embedded market. For the switching function at RF frequency, the RF-MEMS switches offer better performance, such as low insertion loss, high isolation, high bandwidth, and less noise, than standards PIN diode and field effect transistor (FET) switches [11].

Thus, compared to the traditional switches, MEMS switches have several significant advantages for wireless communications and radio frequency technologies [12], [13]. However, they still not reliable and their wide spread commercialization has been limited so far due to some design and operational reasons. The main reasons for that are reliability and yield, as well as, high actuation voltage, large switching time, large size, and packaging [14]. Currently, many research groups around the world are working on new solutions to surmount these problems. In fact, to overcome these challenges, a number of techniques have utilized such as push-pull or meander was fabricated to surpass the problem of switching speed [15]. As well, to decrease the switch actuation voltage, a variety of techniques are employed, including decreasing the spring constant [16], [17], utilizing piezoelectric actuation [18], [19] and other structures [20], [21].

High actuation voltage is one of the most important challenges. A critical aspect of the behaviour of MEMS switch is that the deformation will reduce the distance between the two conductors. This behaviour leads to the phenomenon of pull-in. The increasing of voltage bias will increasingly deform the structure to a point where the deformation will become unstable, then the deformation will increase without the application of any bias until the point of contact between the conductors. Because the distance between the conductors has been dramatically reduced, the applied bias voltage is greater than that required to maintain the contact, so a substantial reduction in the bias voltage is required to allow the mechanical restoring force to again move the structure. This behaviour is the basis for the design of many MEMS because the pull-in voltage is one of the most important parameters of MEMS design [22].

In this paper, a detailed analysis is done to obtain pull-in voltage and optimize the behaviour of the MEMS switch. The pull-in problem of beams cannot be solved analytically as nonlinearity is not taken into account. For this, numerical techniques using finite element analysis (FEA) are adopted. Our contribution is to propose an optimized model that consolidates a compromise between a small area and a reasonable pull-in voltage. For this purpose, we study the MEMS behaviour as a function of some geometrical and mechanical parameters such as length, width, thickness, gap, and Young modulus. Then, we work on these parameters using FEA software called "COMSOL multiphysics" in such a way to decrease the actuation voltage.

2. RESEARCH METHOD

2.1. Principe working of cantilever MEMS switch

Switching is necessary in many applications, both low and high frequency. MEMS switches use mechanical movement to achieve an open or closed circuit in the radio frequency transmission lines. MEMS switch classification depends on the type of geometry, the contact type, the type of configuration, and the type of actuation. In this work, we will design a cantilever MEMS switch with an ohmic contact series configuration. The mechanical motion is achieved using electrostatic actuation for the reason that it is easily integrable, we don't need a specific material but only a voltage source and a metal plate. This type is the simplest to implement for good performance and is the most one that currently mobilizes the research in this field [23], [24]. Its principle is the most convenient for the fabrication that can be compatible with typical RF technologies.

A cantilever is a beam anchored at only one end and free to move at the other end (see Figure.1). In this typical MEMS device, a bias voltage is imposed between two conductors. This causes charge migration that produces an attractive electrostatic force between the two conductors. This force will lead to a mechanical deformation of the cantilever. Normally, this is the principle working that is exploited to achieve the closing of a switch (also to change the position of a mirror). In this case of micromechanical actuators, intermolecular forces such as Casimir and van der Waals forces have been neglected [25]. However, Casimir and van der Waals forces can play an important role in nanobeam actuators. In our work published in 2020 [26], we considered these two effects.

To model the system for dynamic analysis, we use a computationally efficient method. we obtain the grouped parameters of the system and solve it as a parallel-plate capacitor constrained by a spring. By lumped the mechanical elements, the system can be approximated into a single degree of freedom system whose governing as (1).

$$m\frac{d^2z}{dz} = \sum forces \tag{1}$$

Where m is the mass, and z is the displacement of the movable plate.

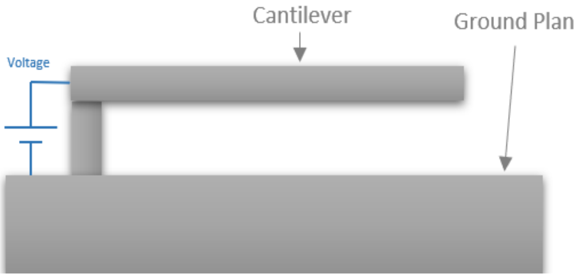

Figure 1. Cantilever MEMS switch

Under the applied voltage V between the two plates, we simulate the cantilever MEMS switch. The metal cantilever ensures the closing or opening of a transmission line. When a potential difference is applied between the electrode and the cantilever, an electrostatic force F_e tends to bring the two conductors closer together. From a certain electrostatic force which corresponds to a voltage called pull-in Voltage Vpull, the cantilever sticks on the conductor.

The electrostatic force generated by the applied voltage, as (2).

$$F_e = \frac{\varepsilon_0 \, AV^2}{2\,(g_0 - z)^2} \tag{2}$$

where V: the applied voltage, A: Air of cantilever, z: the displacement, g0: the initial gap, and εo: permittivity of free space.

The application of an electrical voltage between two electrodes also generates a mechanical force F_m in the opposite direction to the electrostatic force. The corresponding stiffness is k. The force F_m is proportional to z, as (3).

$$F_m = -k \tag{3}$$

By substituting the formulas of the forces in (1), we will have (4).

$$m\frac{d^2z}{dz} = F_e + F_m \tag{4}$$

In order to realize the deformation of MEMS switches, the mechanical behaviour of switch can be modelled using a linear spring constant, k(N/m) and it is given by (5),

$$k = \frac{2}{3} \times M \times w \times \left(\frac{t}{l}\right)^3 \tag{5}$$

where M= Young’s Modulus, w=width of cantilever, t = thickness of cantilever and l = length of cantilever [27]. At equilibrium, we have: $F_e = F_m$.

If the electrostatic force is increased by increasing the applied voltage and if that force is greater than the elastic restoring force, the equilibrium is lost and the cantilever will bend and finally makes contact with the fixed ground plate. This phenomenon is known as pull-in. Therefore, we calculate the actuation voltage V_{pull} at equilibrium and find as (6).

$$V_{pull} = \sqrt{\frac{8kg_0^3}{27\varepsilon_0 A}} \tag{6}$$

V_{pull} depends on the geometrical parameters of the cantilever as well as on the mechanical parameters such as the k-parameter, which in turn depends on Young's modulus M. In order to determine the pull-in voltage of the MEMS cantilever, a FEA software is adopted. The impact of the geometrical and mechanical parameters on the V_{pull} will be studied in the following sections.

The moving element deforms up to the point of instability. This point can be expressed by a certain distance which is calculated: Under static equilibrium, F_m has equal magnitude but opposite direction as the electrostatic force F_e. Thus, at the equilibrium position: $F_m = F_e$. By substituting (2) and (3) in the previous equation, we will have (7).

$$-2kg^2(g_0 - g) = \varepsilon_0 AV^2 \tag{7}$$

Pull-in phenomena will occur when the derivative of voltage with respect to displacement z is zero.

$$\frac{dV}{dz} = 0$$

And the instantaneous g depends on displacement z:

$$g_0 - g = z$$

So, the previous equation can be derived, which yields the following equation:

$$\frac{d}{dz}\{-2kg^2(g_0 - g)\} = \frac{d}{dz}\{\varepsilon_0 AV^2\} = 0$$
$$g = \frac{2}{3}g_0$$

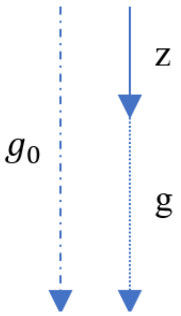

Figure 2. Relationship between the z-displacement, the instantaneous gap and the initial gap

Thus, the pull-in displacement is (see Figure 2):

$$|z_{pull}| = \frac{1}{3}\ g_0$$

The position of z_{pull} :

$$z_{pull} = -\frac{1}{3}\ g_0 \tag{8}$$

The pull-in displacement is determined by the initial gap. In terms of beam instantaneous gap, it corresponds to $^2/_3$ of the initial gap g_0.

2.2. COMSOL modeling

The model of the cantilever is made using COMSOL multiphysics software (see Figure 3). COMSOL was chosen as it allows us to simulate several physical phenomena (coupled or uncoupled) in the same simulation environment. In this work, COMSOL was helpful to model the evolution of the MEMS switches. this tool offered us an interface to make a 3D mechanical drawing of the different parts, namely the cantilever and the ground plane. Also, it allowed us to apply electrical constraints such as the activation voltage to measure the displacement of the cantilever, the resistance or the capacitance.

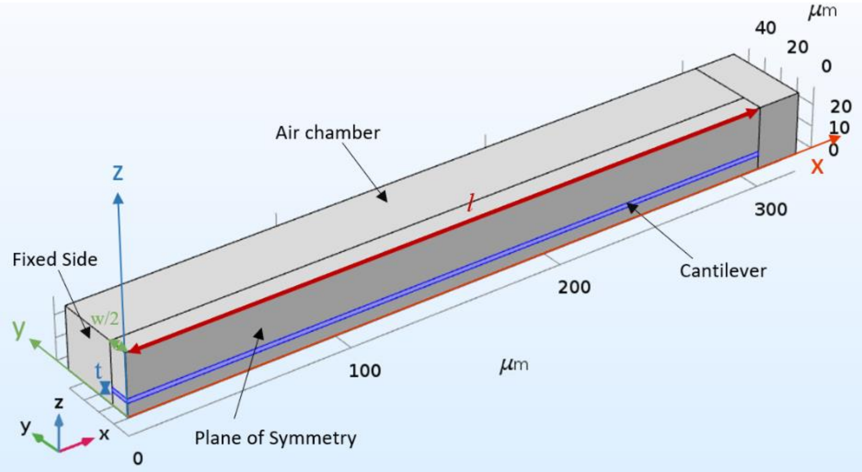

Figure 3. Model of cantilever in COMSOL software

As we mentioned, the behaviour of the cantilever is influenced by its length, width, thickness and the diverse properties of the material utilized to fabricate the structure. The geometric design, as well as the material used to construct the cantilever, affects the applied voltage and in general the stiffness of the cantilever. The analysis is performed on the structure with the parameters indicated in the Table 1.

Table 1. Design parameters of MEMS switch

Cantilever length 1(µm)	Cantilever width w (µm)	Cantilever thickness t (µm)
300	20	2

3. RESULTS AND DISCUSSION

3.1. Impact of mechanical parameters on pull-in voltage

In order to see the impact of the mechanical aspect on V_{pull}, we keep the same geometry defined in the previous section and we compare different materials defined by their Young's modulus M. In this simulation, aluminium, copper, gold, platinum, nickel and molybdenum metals have been used as the materials of cantilever MEMS switches.

We start by simulating aluminium cantilever (M=70 GPa) and describing the results shown in figures. Hence, all other materials simulations results will be presented in a summary table.

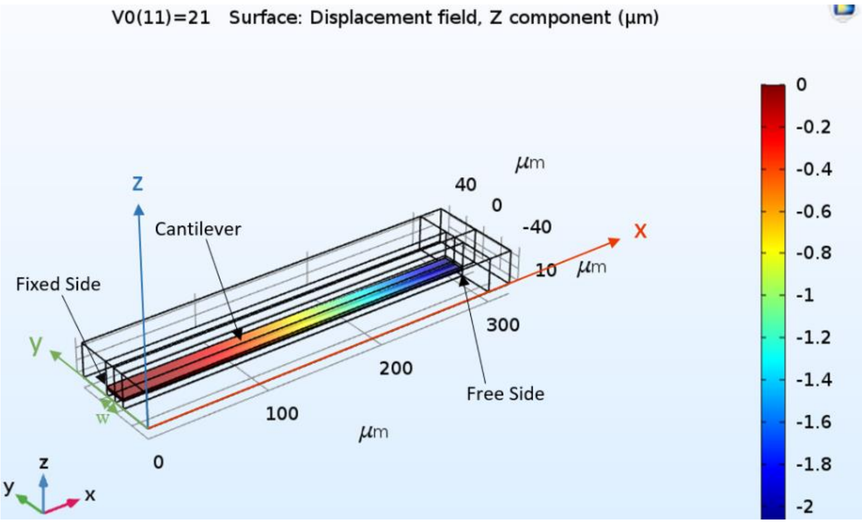

Figure 4. The z-displacement of the cantilever when applied voltage equals to Vpull

As previously mentioned, we maintain the same dimensions presented in Table 1 and we simulate the z-displacement of the cantilever at the limit of symmetry. Figure 5 shows the shape of the cantilever deformation for each applied voltage.

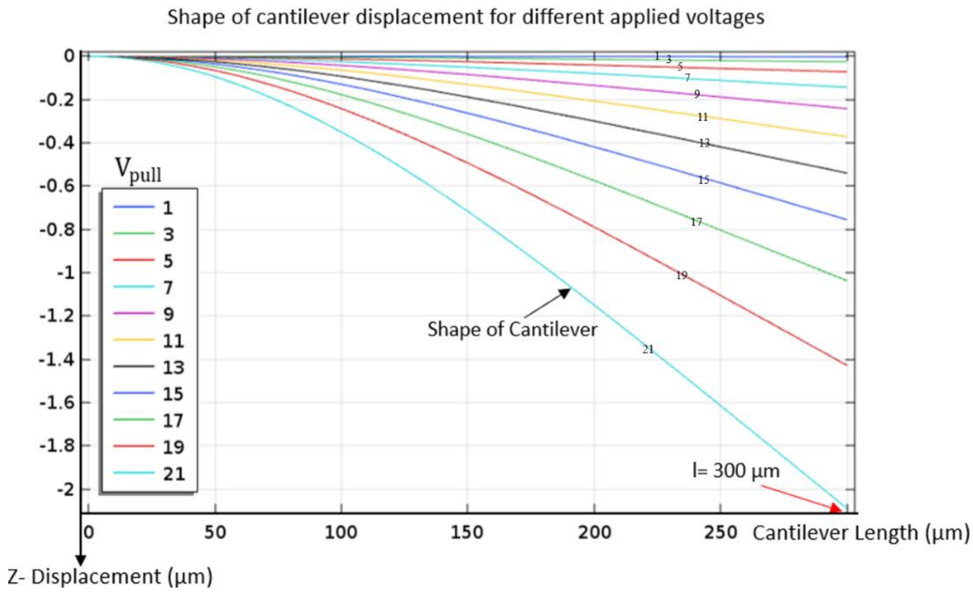

Figure 5. Shape of cantilever displacement for different applied voltages

As we presented, we made our geometry with a gap $g_0 = -6\mu m$, as soon as the cantilever is bent to one third of initial distance $-2\mu m$, automatically it is considered as in a low state. Thus, the pull-in voltage will be calculated at this pull-in position $z_{pull} = -2\mu m$. The pull-in voltage for a device can be determined by identifying the greatest voltage bias that can be supported before pull-in happens.

Viewing the figure, the voltage is plotted against z in which beam bends. At a voltage close to 21 V, we can reach the $z_{pull} = -2\mu m$ and hence the low state. The exact value of the voltage can be determined from Figure 6.

We simulate the displacement of the endpoint of the cantilever as it belongs to the contact surface and has the maximum constraints. We obtain the function shown in Figure 6. It presents the z-displacement as a function of the applied voltage.

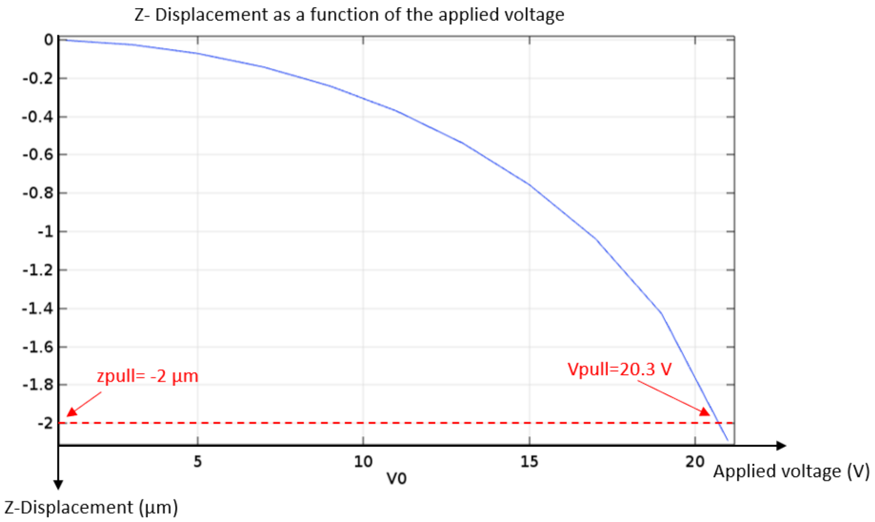

Figure 6. Displacement as a function of the applied voltage.

The value of the voltage corresponding to zpull is equal to 20.3 V. Therefore, to activate our cantilever mems, we have to apply a voltage Vpull which is about 20.3 V. In this work, we take the initial gap $g_0 = -6\mu m$. Therefore, as we demonstrated in the above section, the pull-in position: $z_{pull} = -2\mu m$. We conclude that the pull-in voltage using aluminium cantilever is $V_{pull} = 20.3V$. This simulation is just for aluminum. Now, we will present a summary table to display the simulation results for other materials.

Results Tabulation:

In the Table 2, we can see the calculated and simulated results of the proposed model. For a comparative study, we determined the pull-in voltage formula by substituting the value of z_{pull} into (6). Then, we calculated the values shown in Table 4. Here, we maintain the same geometry and compare different materials described by their Young's modulus M. Therefore, we can identify the impact of mechanical aspect on V_{pull}. Indeed, we deduct from Table 4 that as Young's modulus increases, the Vpull also increases.

Table 2. Young's modulus and pull-in voltage of the different cantilever materials

Metal cantilever	Young's modulus [GPa]	Calculated Vpull (V)	Simulated Vpull (V)
Aluminum (Al)	70	18.253	20.3
Gold (Au)	71	18.383	21
Copper (Cu)	120	23.899	26.8
Platinum (Pt)	168	28.277	31.7
Polysilicon (Poly-Si)	169	28.361	31.7
Nickel (Ni)	219	32.285	36.2
Molybdenum (Mo)	312	38.535	43.2

Now, we will draw a figure of the results in order to see the law that links the mechanical parameter and the actuation voltage and to see the gap between the two curves of the calculated and simulated V_{pull}. In Figure 7, both curves have the same trend and the same overall behaviour. Moreover, there is a gap between the calculated and simulated V_{pull} voltages but this gap does not call into question our simulation. From the obtained results, we can see that aluminium and gold correspond to the lowest value of the V_{pull} voltages. In addition, as mentioned, the simulated Pull-in voltages are in good agreement with the literature values, which confirms the model validity.

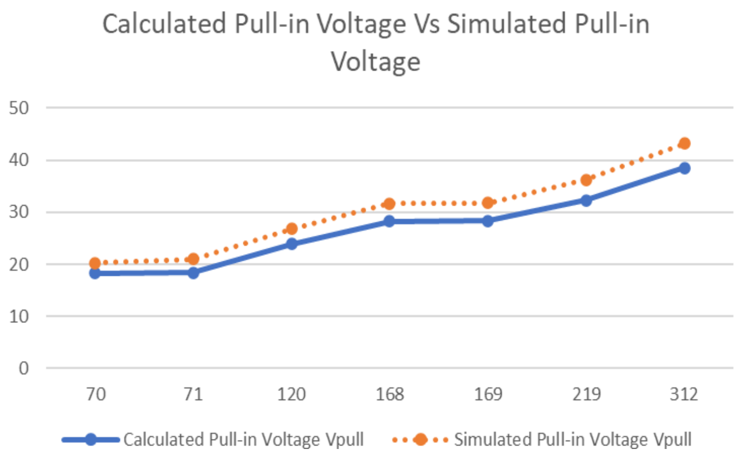

Figure 7. Calculated pull-in voltage vs simulated pull-in voltage

Aluminium and gold are the most ideal materials for the cantilever. However, for technological reasons, it is more desirable to use aluminium. Firstly, from a technological point of view it is easy to integrate. Secondly, it is less expensive. On the other hand, Gold is more expensive and its manufacturing process is more complex as it does not adhere easily to such a layer. Aluminium also has problems as it oxidises easily. Moreover, both aluminium and gold can't resist the temperature. In the present work, we will choose aluminium as a material for cantilever MEMS switches.

3.2. Impact of geometrical parameters on pull-in voltage

Now, to see the impact of the geometric aspect on V_{pull}, we will always take aluminium as the cantilever material and vary the dimensions of the geometry (See Figure 8). The effect of the length l of the cantilever on the pull-in voltage has been studied and based on the simulation results presented in Table 3.

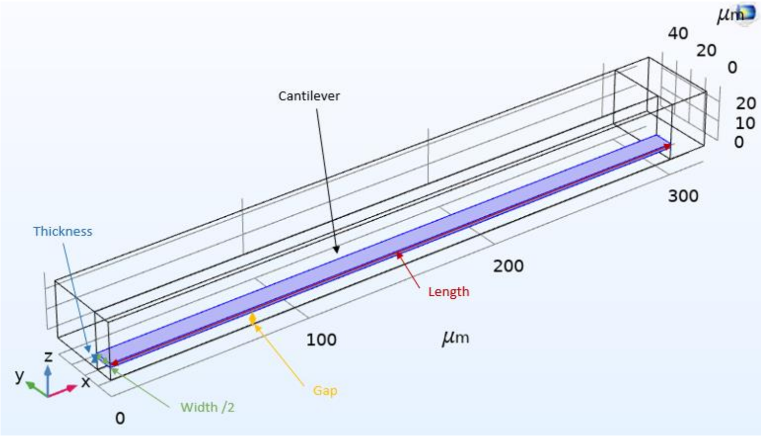

Figure 8. COMSOL model described by its geometric parameters

Table 3. Impact of length on pull-in voltage

Impact of geometrical parametrs	Cantilever length (µm)	Vpull (V)
Impact of length	200	46
	300	20.3
	400	11.5
	500	7.3

It is found that the cantilever length has an inverse relationship with the pull-in voltage V_{pull}. Indeed, we can see, from (6) in section 1, a coherence between the theorical and experimental results. The length is inversely proportional to the spring constant and the spring constant is directly proportional to Vpull. Therefore, the increase in length decreases the spring constant and, consequently, the Vpull decreases.

From Table 4, we can see that a small change in thickness plays a major role in the variation of V_{pull}. The decrease in thickness decreases the spring constant and, consequently, the Vpull decreases. Indeed, from (5) and (6), the spring constant k is directly proportional to the thickness the cube and the V_{pull} is also proportional to the square root of k. These formulas confirm the results of the table.

Table 4. Impact of thickness on pull-in voltage

Impact of geometrical parametrs	Cantilever Thickness (µm)	Vpull (V)
Impact of thickness	1.5	13
	2	20.3
	2.5	28.6
	3	37.6

From Table 5, the width W of the cantilever is having no much effect on modifying the V_{pull}. Indeed, by substituting the formula of k into the formula of V_{pull} (5) and (6), and the air A by its detailed formula. Table 6 shows the impact of gap on pull-in voltage.

Table 5. Impact of width on pull-in voltage

Impact of geometrical parametrs	Cantilever width (µm)	Vpull (V)
Impact of width	10	19.5
	20	20.3
	30	20.5
	40	21

Table 6. Impact of gap on pull-in voltage

Impact of geometrical parametrs	Cantilever gap (µm)	Vpull (V)
Impact of gap	4	11.3
	6	20.3
	8	30.9
	10	42.5

We can see that the width will be reduced. Thus, V_{pull} does not depend on the width. This shows the validity of our results.

$$V_{pull} = \sqrt{\frac{16\times M\times(t\times g_0)^3}{81\times\varepsilon_0\times l^4}} \tag{9}$$

The V_{pull} voltage can also be reduced by decreasing the air gap. This relationship can be confirmed based on (6). It can be concluded that any variation of the geometrical parameters such as length, width, thickness and gap, or the mechanical parameters including Young's Modulus, may result in a significant change of the pull-in voltage.

From the results, to optimize the MEMS switch performances, we need a typical compromise between small area and acceptable pull-in voltage. It can be seen that the best actuation voltage occurs with the geometrical parameters of MEMS cantilever, 400 µm in length and 1.5 µm in thickness. For RF applications, it is recommended to use a large gap of 6 µm to prevent radio frequency interferences. Thus, we work on mechanical and geometrical parameters of a cantilever in such a way to decrease the actuation voltage and improve the power consumption. In addition, low pull-in voltage makes the MEMS cantilever susceptible to self-actuation at high RF power levels. Regarding the used material in manufacturing process for RF applications, aluminium and gold are the most ideal materials to minimize V_{pull} . In the present work, we have worked with aluminium, but in future work, we will adopt gold and elaborate a complete comparison between aluminium and gold cantilever by acting on other technological parameters. Thus, depending on our application, we can modify these parameters in order to obtain the optimized switch model.

The works [28]–[31] are selected for comparison due to the reason that all the switches have cantilever configuration, and they are simulated in order to study their behaviour characteristics, for which the difference between them in the dimensions of the beams is considered. The work [28]–[31] uses very small dimensions that do not meet the needs of our specifications. Typical dimensions of designed switch beam lengths are ranging from 200 to 400 µm, thickness ranging from 1.5 to 3 µm, width ranging from 10 to 40 µm, and gap ranging from 4 to 10 µm. These dimensions are relatively large and are suitable for easy and fast manufacturing. Moreover, by adopting these dimensions, we will avoid the problems of RF interference. Due to these reasons, our model is best suited to manufacturing contraints.

4. CONCLUSIONS

The keen embedded MEMS are one of the rapidly developing technologies in the present embedded market. For this reason, developers and designers have encountered several problems in the modeling of embedded MEMS. In this paper, A COMSOL-based finite element analysis was used to investigate the structure deflection. We analyzed the impact of mechanical and geometrical parameters on the pull-in voltage of the cantilever. The first study of the impact of the mechanical aspect on V_{pull} allowed us to define the material we will use, while the second study of the impact of the geometrical aspect on Vpull allowed us to determine the values of the geometrical parameters that minimize V_{pull}.

In future work, we compare this work by choosing the aluminium cantilever with the gold cantilever by acting on other technological parameters. Also, we correlate all the parameters to find the optimal model that minimises V_{pull} as much as possible and gives the best functioning. The results obtained from this work would allow us to refine and develop improved RF MEMS switches for a wide range of applications.

ACKNOWLEDGEMENTS

The authors thank the referees very much for their constructive suggestions, helpful comments and fast response, which led to significant improvement of the original manuscript of this paper.

REFERENCES

[1] C. T. Nnodim, M. O. Arowolo, B. D. Agboola, R. O. Ogundokun, and M. K. Abiodun, "Future trends in mechatronics," *IAES International Journal of Robotics and Automation (IJRA)*, vol. 10, no. 1, p. 24, Mar. 2021, doi: 10.11591/ijra.v10i1.pp24-31.

[2] P. Kumari, K. Singh, and A. Singal, “Reducing the hygroscopic swelling in MEMS sensor using different mold materials,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 1, p. 494, Feb. 2020, doi: 10.11591/ijece.v10i1.pp494-499.

[3] M. Tecpoyotl-Torres, R. Cabello-Ruiz, P. Vargas-Chable, J. G. Vera-Dimas, and A. Ocampo-Diaz, “Performance of compliant mechanisms applied to a modified shape accelerometer of single and double layer,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 6, pp. 4675–4683, 2019, doi: 10.11591/ijece.v9i6.pp4675-4683.

[4] A. Joshi, S. Redkar, and T. Sugar, “Characterization of capacitive comb-finger MEMS accelerometers,” *Bulletin of Electrical Engineering and Informatics*, vol. 4, no. 4, pp. 320–333, 2015, doi: 10.11591/eei.v4i4.546.

[5] M. K. Naji, A. D. Farhood, and A. H. Ali, “Novel design and analysis of RF MEMS shunt capacitive switch for radar and satellite communications,” *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 15, no. 2, pp. 971–978, 2019, doi: 10.11591/ijeecs.v15.i2.pp971-978.

[6] O. El Maleky, F. Ben Abdelouahab, M. Essaaidi, and N. Abdelfatah, “Miniature design of T-Shaped frequency reconfigurable antenna for S-Band application using switching technique,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 7, no. 5, p. 2426, 2017, doi: 10.11591/ijece.v7i5.pp2426-2433.

[7] G. Quoc-Anh, N. Dinh-Chinh, T. Duc-Nghia, T. Duc-Tan, K. T. Nguyen, and K. Sandrasegaran, “Wireless technology for monitoring site-specific landslide in Vietnam,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 6, pp. 4448–4455, 2018, doi: 10.11591/ijece.v8i6.pp4448-4455.

[8] P. Sattayasoonthorn, J. Suthakorn, and S. Chamnanvej, “The development of a wireless LCP-based intracranial pressure sensor for traumatic brain injury patients,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 2, pp. 1229–1238, 2020, doi: 10.11591/ijece.v10i2.pp1229-1238.

[9] Mr.V.Hari Prasad, M. A. K. Yadav, and D. T. Srinivasulu, “Embedded MEMS : A New Era in Mobile Technology,” vol. 3, no. 2, pp. 857–862, 2013.

[10] N. Kassri, A. Ennouaary, S. Bah, and H. Baghdadi, “A review on SDR, spectrum sensing, and CR-based IoT in cognitive radio networks,” *International Journal of Advanced Computer Science and Applications*, vol. 12, no. 6, pp. 100–121, 2021, doi: 10.14569/IJACSA.2021.0120613.

[11] R. Sharma and D. R. Shah, “Design and analysis of MEMS capacitive shunt type switch for RF application,” *International Journal of Engineering Sciences & Research Technology (IJESRT)*, vol. 5, pp. 179–184, 2016.

[12] D. Klaitabtim and A. Tuantranont, “Design consideration and finite element modeling of MEMS cantilever for nano-biosensor applications,” *2005 5th IEEE Conference on Nanotechnology*, vol. 1, pp. 311–314, 2005, doi: 10.1109/NANO.2005.1500758.

[13] A. Khairy, A. Seoud, A. K. Mahmoud, and A. E. S. Hafez, *Optimized architectures for cantilevered beam RF MEMS switch*. 2014.

[14] J. Naghar, O. Aghzout, and A. Naghar, “Design study of a miniaturized multi-layered antenna-in-package for 2.4 GHz wireless communication,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 5, pp. 3627–3635, 2018, doi: 10.11591/ijece.v8i5.pp3627-3635.

[15] S. P. Pacheco, L. P. B. Katehi, and C. T. C. Nguyen, “Design of low actuation voltage RF MEMS switch,” *IEEE MTT-S International Microwave Symposium Digest*, vol. 1, pp. 165–168, 2000, doi: 10.1109/mwsym.2000.860921.

[16] C. L. Dai, H. J. Peng, M. C. Liu, C. C. Wu, and L. J. Yang, “Design and fabrication of RF MEMS switch by the CMOS process,” *Tamkang Journal of Science and Engineering*, vol. 8, no. 3, pp. 197–202, 2005.

[17] C. Calaza, B. Margesin, F. Giacomozzi, K. Rangra, and V. Mulloni, “Electromechanical characterization of low actuation voltage RF MEMS capacitive switches based on DC CV measurements,” *Microelectronic Engineering*, vol. 84, no. 5–8, pp. 1358–1362, 2007, doi: 10.1016/j.mee.2007.01.196.

[18] J. H. Park *et al.*, “A fully wafer-level packaged RF MEMS switch with low actuation voltage using a piezoelectric actuator,” *Journal of Micromechanics and Microengineering*, vol. 16, no. 11, pp. 2281–2286, 2006, doi: 10.1088/0960-1317/16/11/005.

[19] P. Sagar and B. Jaymin, “Near optimal receive antenna selection scheme for MIMO system under spatially correlated channel,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 5, p. 3732, Oct. 2018, doi: 10.11591/ijece.v8i5.pp3732-3739.

[20] J. Park, E. S. Shim, W. Choi, Y. Kim, Y. Kwon, and D. IL Cho, “A non-contact-type RF MEMS switch for 24-GHz radar applications,” *Journal of Microelectromechanical Systems*, vol. 18, no. 1, pp. 163–173, 2009, doi: 10.1109/JMEMS.2008.2011124.

[21] S.-C. Kang, S.-S. Moon, H.-C. Kim, and K.-J. Chun, “See-saw type RF MEMS switch with narrow gap vertical comb,” *JSTS:Journal of Semiconductor Technology and Science*, vol. 7, no. 3, pp. 177–182, 2007, doi: 10.5573/jsts.2007.7.3.177.

[22] T. Purtova and H. Schumacher, “Overview of RF MEMS technology and applications,” in *Handbook of Mems for Wireless and Mobile Applications*, Elsevier, 2013, pp. 3–29.

[23] K. Grenier, “Conception réalisation et caractérisation de structures micro-usinées sur silicium : applications aux micro-systèmes millimétriques,” 2000.

[24] J. Rizk, G. L. Tan, J. B. Muldavin, and G. M. Rebeiz, “High-isolation W-band MEMS switches,” *IEEE Microwave and Wireless Components Letters*, vol. 11, no. 1, pp. 10–12, 2001, doi: 10.1109/7260.905952.

[25] W. M. Zhang, H. Yan, Z. K. Peng, and G. Meng, “Electrostatic pull-in instability in MEMS/NEMS: A review,” *Sensors and Actuators, A: Physical*, vol. 214, pp. 187–218, 2014, doi: 10.1016/j.sna.2014.04.025.

[26] H. Baghdadi, K. Rhofir, and M. Lamhamdi, “Iterative decomposition for simulating the instability of nano-switches,” in *Advances in Intelligent Systems and Computing*, 2020, vol. 1104 AISC, pp. 421–428, doi: 10.1007/978-3-030-36671-1_37.

[27] R. Sha, R. Ghatak, and R. Mahapatra, “Impact of Beam Thickness and Air Gap on the Performance of Cantilever MEMS Switch,” *International Journal of Current Engineering and Technology (IJCET)*, vol. 7109, no. 2. pp. 207–210, 2013.

[28] K. G. Sravani, K. S. Rao, and K. Guha, “New pull-in voltage modelling of step structure RF MEMS switch,” *Microelectronics Journal*, vol. 117, 2021, doi: 10.1016/j.mejo.2021.105264.

[29] K. G. Sravani, C. Gopichand, and K. S. Rao, “Design and analysis of a serpentine type RF MEMS shunt switch with low pull-in-voltage,” *Transactions on Electrical and Electronic Materials*, 2021, doi: 10.1007/s42341-021-00358-5.

[30] Kurmendra and R. Kumar, “Investigations on beam membrane and dielectric materials using Ashby’s methodology and their impact on the performance of a MEMS capacitive switch,” *Microsystem Technologies*, vol. 27, no. 12, pp. 4269–4289, 2021, doi: 10.1007/s00542-021-05220-5.

[31] K. G. Sravani, T. L. Narayana, K. Guha, and K. S. Rao, “Role of dielectric layer and beam membrane in improving the performance of capacitive RF MEMS switches for Ka-band applications,” *Microsystem Technologies*, vol. 27, no. 2, pp. 493–502, 2021, doi: 10.1007/s00542-018-4038-4.

BIOGRAPHIES OF AUTHORS

Hajar Baghdadi a Ph.D. Student at the Faculty of Technical Sciences (Hassan 1st University, Settat, Morocco). She received her engineering diploma in Electrical Engineering in 2016 from the National School of Applied Sciences of Khouribga. Her main research interest includes Embedded Systems and MEMS Technology. She can be contacted at email: h.baghdadi@uhp.ac.ma.

Mohamed Lamhamdi an Associate Professor at the Faculty of Technical Sciences (Hassan 1st University, Settat, Morocco). He received his Ph.D in Materials and Technology of Electronic Components in 2008 from the Paul Sabatier University, Laboratory for Analysis and Architecture of Systems (LAAS), Toulouse, France. From 2008 to 2012, he was a researcher in the LMP STMicroElectronics, Tours. In 2012, he became an Assistant Professor at the National School for Applied Sciences, Khouribga, Morocco, where he became an Associate Professor in 2016. In January 2018, he joined the Faculty of Technical Sciences, Settat, Morocco. His research interests include Material Characterization, MEMS/NEMS Technology, Thin Films and Nanotechnology. He can be contacted at email: mohamed.lamhamdi@gmail.com.

Karim Rhofir earned his B.Tech., from, AMU, Aligarh in 2001, M.Tech. (Digital Systems), from MNNIT, Allahabad, in the year 2003 and completed his Ph.D. from Jamia Millia Islamia (A Central University) in 2019. He is currently working as Faculty member in Department of ECE in SEECE, Galgotias University. He has published several research papers in various International Journals and International/National conferences, has also attended several national and international conferences and workshops. He was technical committee members of many international conferences, including ICEEE2020, RDCAPE2019, NANOfIM2017, GUCON 2019. He has received best paper award in INDICON 2015. He is a member of IEEE. He can be contacted at email: rashid.vns@gmail.com.