Design and Simulation of a Micro-Electro-Mechanical Switch

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Abstract

This study contains the design and simulation of a MEMS switch for a micro piezoelectric voltage generator system. This switch is electro-statically actuated by the voltage generated by the micro piezoelectric system that has a low range as 0.6-1V. Thus, an optimization is required to decide the size of the switch and the material to be used that are suitable for pull-in voltage range. In this optimization, a closed form model of pull-in voltage is used. The switch should work far away from resonant frequencies. Due to this constraint, a resonant frequency analysis must be investigated and it is required to decide which sizes and materials are convenient. Also, the system needs an ideal switch meaning that it should have a low resistance. What is more, we want the switch to have a hysteretic behavior meaning that pull-in and pull-out voltages should be different. As the system will work in a vibrating environment, not only electrical but also mechanical analyses like tip deflection analysis and response under instant accelerations play a big role to decide whether the switch pulls in below the required voltage, or not.

1. Introduction

In recent decades micro-electro-mechanical systems (MEMS) have been used in novel devices of various defense, medical, and commercial applications because of their low cost, miniature size, low-energy consumption, and life-time [1]. Another fast moving and value pursuing area is micro energy generating devices which hold great promise for wireless sensor networks and communication circuits. Batteries and fuel cells are not useful for applications in communication devices regarding their large size and hard integration to wireless networks [2].

The interest of this study lays in the design of a MEMS switch for a micro piezoelectric power generating device. The main component of this system is a MEMS device. When the system vibrates or is under pressure, an alternating voltage is generated. Thus, a MEMS switch is required for this system. Due to their advantages like low-power consumption, high isolation, MEMS switches replace the conventional switches. The pull-in phenomenon that will be examined in this research occurs under electrostatic actuation. Also, fundamental frequencies of MEMS switches will be observed. As the voltage generating device will be in a vibrating environment, some dynamic analysis such as tip deflection and acceleration responses will be investigated for different materials.

2. The system concerning MEMS switch

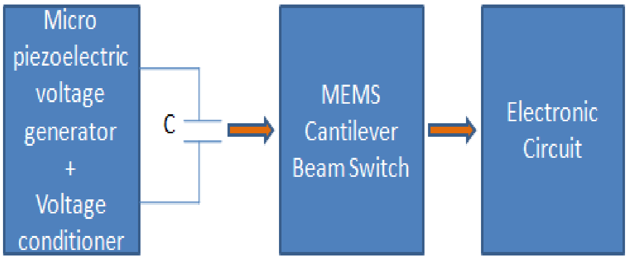

Fig. 1. System Overview

The ultimate goal of this investigation is to design a MEMS switch for a micro piezoelectric voltage generating system which is required to act as an ideal switch whose resistance will be very low. One of the main components of the system as illustrated in Figure 1 is a micro-electro-mechanic device which has been fabricated with piezoelectric material [2]. So, under vibrations it oscillates and the stress on the piezoelectric material generates an alternating voltage. This voltage is rectified by a voltage conditioner and stored on a capacitor C. Due to the fact that the voltage on that capacitor changes related to the circuit loading and vibration amplitude, a voltage-controlled switch is required. When the required operational voltage level is reached, this switch connects the capacitor to the circuit. When the voltage level is less than this point, the switch is off and the storage capacitor is charged. The peak-to-peak AC voltage levels of 0.6-1V are possible to be generated by the system [2]. In this study, the needed MEMS switch is optimized and designed after some observations for pull-in analysis, resonant frequency analysis, effect of the different sizes of the switch, tip deflection analysis, analysis for different materials, maximum deflection under acceleration, and hysteresis, resistance considerations.

3. Pull-in voltage analysis

Before designing a MEMS device, it is prominent to understand this phenomenon. When a voltage is applied to parallel plates, electrostatic force occurs and reduces the gap between these two plates. If voltage increases, eventually two plates touch together. This phenomenon is known as ‘pull-in,’ and the critical voltage associated with it is called ‘pull-in voltage’ [1]. A closed form model for pull-in voltage is given in [3] as

$$V_{PI} = \sqrt{\frac{2\tilde{E}h^3 d_0}{8.37\varepsilon_0 l^4\left(\frac{5}{6(d_0)^2} + \frac{0.19}{(d_0)^{1.25} w^{0.75}} + \frac{0.19}{(d_0)^{1.25} l^{0.75}} + \frac{0.4h^{0.5}}{(d_0)^{1.5} w}\right)}} \quad (1)$$

where, l, w, h, d_0, and $\tilde{E}$ represent beam length, width, thickness, initial gap, and effective modulus respectively. Here, we use this closed form model of pull-in voltage to optimize the size of required cantilever beam for a micro voltage generating system producing approximately voltage ranges of 0.6-1V. Also, effects of different sizes and different materials on the pull-in point are examined. Due to the design constraints, the maximum voltage can be produced by micro voltage generator device is 1 Volt. Polysilicon can be used to fabricate the cantilever beam. Two cases can be checked for fixed thickness (h) value and different values of initial gap (d_0) as in Table 1. We have optimized the width and length for the cantilever beam under fixed thickness value for two different initial gap values. By using pull-in voltage closed form formula in Eq.1 and 'Comsol' software, we compared the results of simulation environment and mathematical equation.

Table 1. The optimum values of pull-in voltage, width, length for Polysilicon cantilever beam, regarding to two different values of initial gap for fixed thickness

Common parameters are E = 131 Gpa , ϵ_0= 8.85*10^{-12} Farad/m, ν = 0.27 (Poisson's ratio), d = 2330 kg/m^3 and h = 1μm				
	V_{PI} result of the formula (V)	V_{PI} result of COMSOL (V)	Optimum width (w) (μm)	Optimum length(l) (μm)
Case-1 d_0 = 1 μm	0.9881	0.9849	50	260
Case-2 d_0 = 1.5 μm	0.9978	0.9964	50	350

We can use different materials for the fabrication of the beam like Aluminum and Gold. The results of optimum values for these materials have been obtained as in the Table 2 and Table 3 with 'Comsol' and the formula for pull-in voltage.

Table 2. The optimum values of pull-in voltage, width, length for Aluminum cantilever beam, regarding to two different values of initial gap for fixed thickness

Common parameters are E = 70 Gpa , ϵ_0= 8.85*10^{-12} Farad/m, ν = 0.33, d = 2700 kg/m^3 and h = 1μm				
	V_{PI} result of the formula (V)	V_{PI} result of COMSOL (V)	Optimum width (w) (μm)	Optimum length(l) (μm)
Case-1 d_0 = 1 μm	1.01	1.01	20	220
Case-2 d_0 = 1.5 μm	0.9998	1.003	23	300

Table 3. The optimum values of pull-in voltage, width, length for Gold cantilever beam, regarding to two different values of initial gap for fixed thickness

Common parameters are E = 70 Gpa , ϵ_0= 8.85*10^{-12} Farad/m, ν = 0.44, d = 19300 kg/m^3 and h = 1μm				
	V_{PI} result of the formula (V)	V_{PI} result of COMSOL (V)	Optimum width (w) (μm)	Optimum length(l) (μm)
Case-1 d_0 = 1 μm	0.9897	0.9865	50	230
Case-2 d_0 = 1.5 μm	0.997	0.9955	50	310

The displacement results from Comsol software under the pull-in voltage for cantilever beams made of Polysilicon, Aluminum and Gold for l=260μm, w=50 μm, h=1 μm, d_0=1 μm can be observed as in the Figure 2. Thus, under the same design values making the beam from aluminum brings great advantage regarding the pull-in voltage.

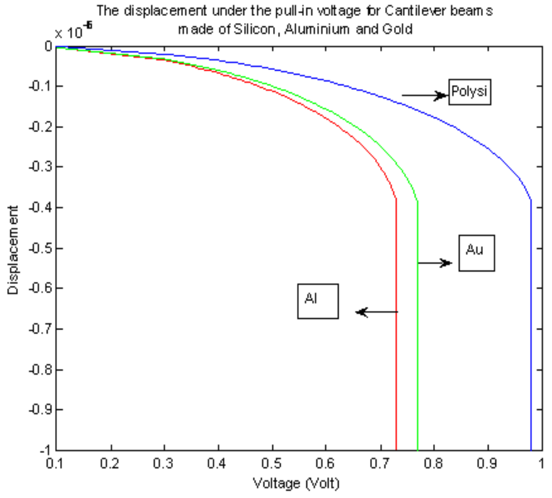

Fig. 2. The pull-in voltage – displacement graph for Cantilever beams made of Polysilicon, Aluminum and Gold for l=260μm, w=50 μm, h=1 μm, d_0=1 μm

4. Resonant frequency analysis

The micro piezoelectric voltage generating device works at frequencies in the range of 100-200 Hz. We should see how different sizes and different materials change their value, and observe if they are suitable for working conditions of the system. The resonant frequency formula for a cantilever beam can be derived as:

$$f_1 = \frac{1}{2\pi}\left[\frac{3.5156}{L^2}\right]\sqrt{\frac{EI}{\rho}} \quad (2)$$

where, *E, I, ρ*, and *L* represent Young's modulus, inertial moment, mass per length, and length of the beam respectively. Due to the pull-in voltage constraint, the optimum design values are found as l=260 µm, w=50 µm, h=1 µm, d_0=1 µm. Resonant frequency values of cantilever beam made of Polysilicon, Aluminum, and Gold for optimum sizes can be seen in Table 4. These results demonstrate that there is no more difference between resonant frequencies of Aluminum cantilever beam and Polysilicon cantilever beam.

Table 4. Resonant frequencies of Polysilicon, Aluminum, and Gold cantilever beams for l=260 µm, w=50 µm, h=1 µm, d_0=1 µm

Cantilever beam material	Resonant frequency (kHz)
Polysilicon	18.607
Aluminum	12.2
Gold	4.55

5. Analysis for tip deflection and acceleration

As the system can be used in environments having vibrations and instant accelerations, the reaction of cantilever beam should be observed under sinusoidal displacements and accelerations. From this observation we will obtain tip deflection of the beam that is the difference between displacements at the free end of the beam and at the fixed end of the beam. Then, we will be able to see whether the switch pulls in before required voltage under vibration. Applying super position method to the tip deflection analysis can be useful that means; firstly, we will assume that voltage is zero and there is a vibration affecting the base of the cantilever beam, then we will assume that there is no vibration and voltage is less than pull-in voltage. After calculating tip deflection for both cases, we will add them to each other that will give us the tip deflection.

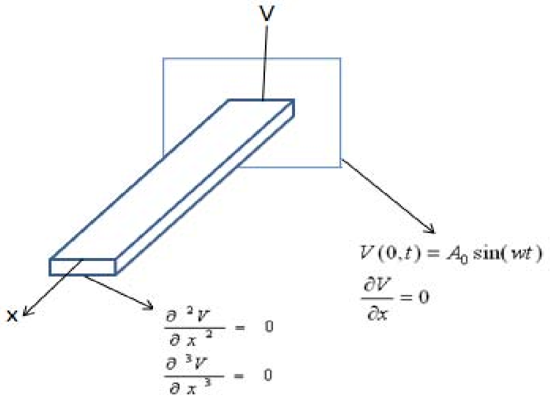

Fig. 3. A cantilever beam being affected by a vibration from its base.

At first, assuming voltage is zero and there is a vibration *v(t)=A₀*sin(w*t*) affecting the base of the cantilever beam as in the Figure 3, we will obtain tip deflection. The tip deflection formula can be expressed as:

$$V(L) = A_0 \frac{\cos kL + \cosh kL}{\cos kL \cosh kL + 1} \tag{3}$$

where,

$$k^4 = \frac{\omega^2 \rho A - j\omega\alpha}{\beta I j\omega + EI} \tag{4}$$

with *ρ* representing the mass density of the beam; *α* is mass damping coefficient and *β* stands for stiffness damping coefficient. While voltage is zero and a vibration of 100 µm amplitude exists at 200 Hz, the tip deflections of cantilever beams made of Polysilicon, Aluminum, Gold for l=260µm, w=50 µm, d_0=1 µm, and h=1 µm are as shown in Figure 4.

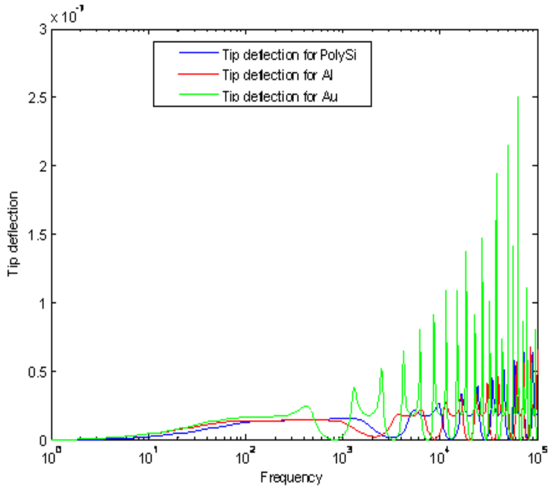

Fig. 4. Tip deflection values of beams made up from three materials for l=260 µm, w=50 µm, h=1 µm, d_0=1 µm, when a vibration affects at base of the cantilever beam that has 100 µm amplitude and 200 Hz frequency

For the case that the voltage is less than pull-in voltage, if a vibration with amplitude of 100 µm and a frequency of 200 Hz affects the base of the cantilever beam, the percentage of pull-in point changes for cantilever beams made of different materials are given in Table 5. Regarding the tip deflection analysis, it can be concluded that it does not make much difference either to produce the cantilever beam from Polysilicon, or from Aluminum or Gold.

Table 5. The comparison of pull-in point changes for conditions under vibration and no vibration

Cantilever beam material	Pull-in voltage (V) (No vibration)	Pull-in voltage (V) (Vibration at 200Hz with 100 µm amplitude)	Pull-in voltage change (%)
Polysilicon	0.98	0.97	1
Aluminum	0.73	0.72	1.37
Gold	0.77	0.76	1.30

Assuming that maximum 10g acceleration affects the base of the beam, the deflection results can be attained as in Table 6. The worst result is for the cantilever beam made of gold and the best results are for the cantilever beams made of aluminum and Polysilicon. Making the cantilever beam from Polysilicon or aluminum seems more advantageous.

Table 6. The Comparison of deflections at 10g for different cantilever beams

Cantilever beam material	Polysilicon	Aluminum	Gold
Maximum deflection at 10g acceleration (μm)	0.03	0.062	0.36

6. Hysteresis and resistance considerations

The cantilever beam that is required for our system does not contain any dielectric space. Also, there is no model for pull-out voltage in the literature for the type of cantilever beams we are interested in. The cantilever beam we are concerned can be seen as a micro relay, so we can take papers that studied the micro relays into consideration. Observed information in [4], [5], and [6] are given in Table 7. Thus, the pull-in and pull-out voltages will be different and the pull-out voltage of our cantilever beam may be assumed as in the region 80% of $V_{pull-in} \leq V_{pull-out} \leq$ 98% of $V_{pull-in}$.

Table 7. Observed information from some papers

	$V_{pull-in}$ (V)	$V_{pull-out}$ (V)	$V_{pull-out} / V_{pull-in}$
Paper [4]	82	76	0.92
Paper [5]	44.5	40	0.89
Paper [6] (asymmetrically)	9.34	9.27	0.98
Paper [6] (symmetrically)	11.89	10.15	0.85

Calculating the resistance of cantilever beams made of Polysilicon, Aluminum, and Gold brings useful information for electrical properties of switching system. We want this switch to act as an ideal switch. Resistivity of polysilicon can be decreased by doping with phosphorus. The maximum phosphorus concentration is 10^{20} cm^{-3} where the resistivity of polysilicon takes its minimum value. Calculated resistance values of cantilever beams can be seen in Table 8. Results in this table show that using Aluminum or Gold to fabricate the MEMS switch is convenient to obtain an ideal switch.

Table 8. Resistance values of cantilever beams

Cantilever beam material	Resistivity of the used material (Ω.m)	Resistance (Ω)
Polysilicon (Phosphorus concentration: 10^{20} cm^{-3})	~1x10^{-5}	52
Aluminum	2.82x10^{-8}	0.2932
Gold	2.44x10^{-8}	0.2537

7. Conclusion

The design and simulation of a micro-electro-mechanic cantilever beam have been investigated for a micro voltage generator device using vibrations, pressure, and instant accelerations as sources. Considering that the micro voltage producing system will be used in vibrating environments and this system needs an ideal switch whose resistance has very low values, results of several analyses indicate that fabricating the cantilever beam from Aluminum with l=260μm, w=50 μm, h=1 μm, d_0=1 μm is the most preferable choice as it is the most suitable one for vibration conditions and voltage range of the micro-electromechanical device. Also, its resistance is around 0.2932 Ω showing that this cantilever beam acts as an ideal switch. Knowing that the pull-in voltage of the Aluminum cantilever beam is approximately 0.73V, our estimation for pull-out voltage is $V_{pull-out} \geq 0.6$V.

The future work includes the fabrication of the cantilever beam and its reliability studies. Fabricated cantilever beam should be tested in vibrating environments and under step accelerations in real conditions.

8. References

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