Design and Optimization of AlN based RF MEMS Switches

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Abstract. Radio frequency microelectromechanical system (RF MEMS) switch technology might have potential to replace the semiconductor technology in future communication systems as well as communication satellites, wireless and mobile phones. This study is to explore the possibilities of RF MEMS switch design and optimization with aluminium nitride (AlN) thin film as the piezoelectric actuation material. Achieving low actuation voltage and high contact force with optimal geometry using the principle of piezoelectric effect is the main motivation for this research. Analytical and numerical modelling of single beam type RF MEMS switch used to analyse the design parameters and optimize them for the minimum actuation voltage and high contact force. An analytical model using isotropic AlN material properties used to obtain the optimal parameters. The optimized geometry of the device length, width and thickness are 2000 \(\mu\)m, 500 \(\mu\)m and 0.6 \(\mu\)m respectively obtained for the single beam RF MEMS switch. Low actuation voltage and high contact force with optimal geometry are less than 2 \(V\) and 100 \(\mu\)N obtained by analytical analysis. Additionally, the single beam RF MEMS switch are optimized and validated by comparing the analytical and finite element modelling (FEM) analysis.

1. Introduction

The RF MEMS switch is the most important MEMS device in the RF/microwave field. A RF MEMS switch is a switching device used in the RF range, which is fabricated using the micromachining technology. More flexible, light weight and low power wireless systems are the usual demand for RF communication that can drastically reduce manufacturing cost, size, weight and improve performance [1] and battery life. Commercialization of RF MEMS switches has several challenges due to high voltage and high power required for the available RF MEMS switches. Due to high voltage requirements, the functional benefit from the RF MEMS switches has been hampered. This power related problems are minimized and various requirements and issues must compare with design parameters to get good performance by the piezoelectric material based RF MEMS switch. Piezoelectric actuation principles seems to be advantageous over the electrostatic actuation for MEMS applications because of the operation with high force, fast speed response with low actuation voltage and easy control, good operational repeatability, high operational efficiency, possibility of static and vibration actuation, lack of dust, radiation and temperature harmfulness features [2, 3]. Various research groups and commercial companies intended to do research on piezoelectric RF MEMS switches based on PZT (Lead zirconate titanate) materials over the last few years. However, for good performance RF MEMS switch, it is necessary to improve the actuation voltage and contact force, which depends on the piezoelectric coefficients of a piezoelectric material. PZT has high piezoelectric coefficients that can increase the contact force and the actuator deflections. Nevertheless, the PZT are not compatible with CMOS. So, based on literature study focusing on various actuation mechanisms...
and analytical calculation it is preferred that the piezoelectric AlN based RF MEMS switch can fulfill good RF performance requirements. Theoretical study has been done in these recent research for electrostatic [6,7], PZT [10, 5] and AlN [3, 4] based RF switches. Considering the RF performance and technological relationship, it is observed that, AlN based RF MEMS switch would be best compare to the electrostatic and PZT based RF MEMS switches.

2. Analytical design and optimization of RF MEMS switches

The analytical solution in this section used the Euler-Bernoulli beam theory because shear deformation is negligible for a long beam. A variable cross-section is used e.g. to reduce the actuation voltage and increase the contact force for a piezoelectric actuated RF MEMS switch. Therefore, several different design approaches are investigated using an analytical design technique based on 3-D piezoelectric single beam RF MEMS switches. Because of this hypothesis, strain distribution within the piezoelectric film to be homogeneous. The expression for the average induced voltage and beam displacement for a unimorph multilayer beam, subjected to a static load are discussed and studied in this work. The analytical methods were implemented in MathCad, where a number of parameters can be differed at once. Utilizing this approach, the effect of given parameter could be better comprehended allowing for better optimization of a structure. With a suitably polarized, it is demonstrate the configuration of a basic piezoelectric beam thin-film actuator switch. Here the length and width of the piezo-electric layer and the substrate layer are same in dimension with different thicknesses. The beam deflection is depending on the polarization of the piezoelectric film and actuation voltage. The analysis of such switch used to determine the displacement that can be achieved by the piezoelectric actuation under some conditions. These conditions are studied in this analysis.

Area of the beam substrate layer and piezoelectric layer are expressed by the following equations:

\[ A_b = W_b L_b \]  
\[ A_p = W_p L_p \]  

Here \( A_b \) and \( A_p \) are the area of the substrate and piezoelectric layers respectively. The length and width of the beam substrate and piezoelectric layers are expressed by the \( L_b, L_p \) and \( W_b, W_p \) respectively. The considered beam moment of inertia for the substrate layer \( I_b \) and piezoelectric layer \( I_p \) are expressed by the following equations:

\[ I_b = W_b t_b^3 / 12 \]  
\[ I_p = W_p t_p^3 / 12 \]  

Where, \( t_b \) and \( t_p \) are the substrate and piezoelectric layers thickness of the single beam RF MEMS switch.

In the piezoelectric single beam RF MEMS switch, the strain distribution on the piezoelectric layer is dominated by the deflection pattern of the substrate. As a result, the free piezoelectric strain \( \varepsilon_0 \) is linearly distributed over the substrate, which can be expressed by the equation 5 [8].

\[ \varepsilon_0 = V d_{31} / t_p \]  

The AlN base single beam RF MEMS switch piezoelectric bending moments \( M_i \) can be described as [9].

\[ M_b = \frac{1}{1 + E_p t_p / E_b t_b^2} \left[ \frac{1}{E_p A_p} + \frac{1}{E_b A_b} \right] \left[ \frac{L_b^2}{4E_b b} + \frac{L_p^2}{4E_p p} \right] \left[ \frac{L_b t_p}{4E_p p} - \frac{L_p t_b}{4E_b b} \right] + \left[ \frac{L_b^2}{4E_b b} \right] \left[ \frac{L_b t_b}{4E_b b} \right] \frac{L_p - t_p}{L_b + L_p} \]  

Here \( E_b \) and \( E_p \) are the young modulus of substrate and piezoelectric layer respectively. The above equations that are used to calculate the static deflection of a single beam RF MEMS switch actuated by a piezoelectric actuation can be calculated by:

\[ \text{Disp} = M_b L_b^2 / 2E_b I_b \]  

The displacement analysis of single beam RF MEMS switches are studied by equation 7. Figure 1 shows single beam piezoelectric RF MEMS switch displacement, which increase as the beam length
increase with the substrate layer thickness. But, in contrast to piezoelectric layer of the RF MEMS switches, higher displacement obtained for the thinner piezoelectric layer over the substrate layer shown in figure 2. Displacement as a function of applied voltage correspond to beam length also studied and observed that, larger displacement is obtained for the higher voltage for longer beam length. This analytical analysis represents the behaviour of various geometrical influences and effect of voltage loading on displacement for the single beam RF MEMS switches in piezoelectric actuation. So, multilayer beam actuated by the piezoelectric layer RF MEMS switches significantly depends upon the original length of the beam, substrate thickness, thickness of the piezoelectric layer and applied voltage.

2.1. Analytical voltage analysis

The RF MEMS switch performance are depends on the actuation voltage of the device. So it is necessary to minimize the voltage to get good RF performance of MEMS switches. In order to lower the actuation voltage of the MEMS switch, three main different rules can be followed: 1) designing a structure with a low spring constant; 2) decreasing the gap between the membrane and the bottom electrode; and 3) increasing the effective actuation area [1]. The first one is the most flexible, because the design of the springs constant does not considerably impact the size and weight of the RF performance and its circuits. In the second case, the isolation associated with the RF signal, which depends on the gap size. And the third one is the effective area of the piezoelectric actuation electrodes, which is limited with regard to the total area of the device. Most of these parameters are directly linked to each other. As an example, if it decreases the gap or raise the area of the piezoelectric and substrate layer, this results increase of off capacitance, leading to a poor isolation. So, there is a certain limit to decrease the gap size. A factor (K) is required to estimate the actuation voltage for the single beam RF MEMS switch that include the geometrical and material constants.

\[
K = \frac{t_b}{2t_p} + \frac{1}{E_b(W_b t_b)} + \frac{1}{E_p W_b t_p} + \frac{t_b^2 + t_p^4 b}{4E_b I_b} + \frac{1}{E_p W_b t_p} \tag{8}
\]

The actuation voltage are explain by the equation 8 and equation 9 [9].
2.2. Analytical Contact force analysis
The contact force analysis is necessary for the control and reduced the contact resistance that is desirable for the good performance RF MEMS switches. The gap size is also an important parameter for the contact force analysis. The initial gap “G” is usually fixed by the required isolation loss between the switch contact electrodes. It is investigated that, the contact force is inversely proportional to the gap size. The Gap size can be calculated by the equation 10 [8].

\[
G = \frac{M_e}{2(\varepsilon_l)} L^2 - \frac{F_c}{3(\varepsilon_l)} L^3 \quad (10)
\]

So, the contact force analysis for a single beam RF MEMS switch structure can be derived as:

\[
F_c = \left[ \frac{M_e L^2}{2(\varepsilon_l)} - G \right] \frac{3(\varepsilon_l)}{L^3} \quad (11)
\]

Figure 3 illustrate that, after a certain substrate thickness, the contact force will be decreasing and every 100 µm substrate width increase, the contact force will increase almost double. It can also demonstrated that, the contact force decreases after a certain substrate layer thickness. So, the contact force analysis of the geometrical parameters for the RF MEMS switch is really difficult. To get the maximum contact force it is necessary to optimize the geometrical parameters.

3. Optimization of geometry for minimum voltage and high contact force

3.1. Minimum voltage optimization
All geometrical parameters must fulfill the fabrication requirements, which are the major considerations of the geometrical design for RF MEMS switches. This research will introduce the
various analytical analysis to minimize the actuation voltage by finding the optimal geometrical parameters. From the figure 4 it can be illustrated that, the higher substrate thickness needs higher voltage for actuation. It can be stated that, the thickness of the substrate layer is more impacting on the voltage than the width of the substrate layer size. This validates the previous discussion (selecting the substrate thickness). From the analysis, it also observed that single beam piezoelectric RF MEMS switch actuation voltage will decreased as the beam length increases. The actuation voltage reduces to less than 1 Volt is obtained from the beam width of 500 µm with the length of 2000 µm for a certain thickness of the beam. After that, as the substrate layer thickness of the RF MEMS switch increase, the actuation voltage will also increase. As discussed before, the substrate layer thickness should be sufficiently thin for the piezoelectric actuation. Therefore, the beam length of 2000 µm with the substrate thickness of the 50 µm are considered as optimal parameters for the minimum actuation voltage.

These geometrical parameters will be suitable for the AlN based piezoelectric actuation and the minimum voltage of less than 2 Volt is considered for the optimum actuation voltage. It is also satisfy the increasing effective actuation area for minimizing the actuation voltage. As it is previously discussed that, decreasing the gap between the beam and the bottom electrode which lead to minimize the voltage. This statement validated by the figure 5. Higher gap size needs higher voltage to actuate the single beam RF MEMS switches. The gap size of 500 nm considered as the optimal gap for the minimum actuation voltage.

Analysis also done for the optimization of piezoelectric coefficient. From this analysis it can be explain that, the minimum voltage also depends on the piezoelectric coefficient along with the geometrical cross-section. RF MEMS switch actuation voltage can be minimized by increase the piezoelectric coefficient. But it is limited by the some certain value of piezoelectric coefficient ($d_{31}$) which can be obtained from the material selection. After a certain limit, if the piezoelectric coefficient increases, the minimum voltage will not be decreased significantly. It can be described that, the voltage of the RF MEMS switches depend on the piezoelectric coefficient ($d_{31}$), which could be determined during the deposition process. So, after the analytical design analysis, the optimal piezoelectric coefficient is 2.6 (pm/V) considered for this single beam RF MEMS switches study.

3.2. High contact force optimization

![Figure 4](image1.png) **Figure 4.** Single beam RF MEMS switch actuation voltage and substrate thickness relationship by changing beam length.

![Figure 5](image2.png) **Figure 5.** Single beam RF MEMS switch actuation voltage relationship with substrate layer thickness and gap size between the beam and the bottom electrode.
In this analysis, previous analytical design experience used to select the geometrical parameters. From the figure 6 it can be describe that, the contact force 100 - 200 µN is obtained for the optimal geometry. This range of contact force in RF MEMS switch is desirable for the good RF performance [1].

![Figure 6. Contact force relationship with substrate thickness for single beam RF MEMS switch.](image)

Here the gap size between beam and electrode is 500 nm considered. For this case, the piezoelectric co-efficient are considered as 2.6 pm/V and piezoelectric thickness kept constant as 0.6 µm. Based on the presented equation 11, optimization of the contact force analysis of single beam RF MEMS switches are driven by piezoelectric actuator and maximize by given isotropic materials, initial gap and actuation voltage. It is observed that contact force is maximized when the single beam RF MEMS switch length allows a free tip deflection and it is mainly depends on the length and the gap size of the single beam RF MEMS switch.

4. Conformation of modelling tool for RF MEMS switches

Analytical models are extremely useful for a preliminary assessment of RF MEMS switches at the design stage. The analytical solution has an error, because it is an approximate solution of theoretical equations. The solid element type will be a better choice as long as the RF MEMS switch is primarily under bending which were the conditions of the analysis in this section. The majority of the modelling using the analytical methods presented in the previous section. FEM simulations are performed for the electromechanical modelling using the ANSYS platform as conformation modelling. Finally, the optimized analytical results for single beam are used as the reference to check the performance of the FE simulation model. This way of analysis will also validate the analytical result.

4.1. Single beam RF MEMS switch analytical and numerical simulation comparisons

To estimate the piezoelectric single beam RF MEMS switch displacement it is considered the values and proportions of the optimized beam. The analytical analysis and FEM ANSYS solution points of displacement are shown below in subsequent figures. The material properties considered in the ANSYS models are all anisotropic. The anisotropic material properties of Si and SiO$_2$ are taken from the referred paper [11].

The boundary conditions applied to single beam type piezo-electrically actuated RF MEMS switch are shown in the figure 7 (a) and RF MEMS switch FEM model shown in the figure 7 (b). The figure 8 describes the behaviour of voltage loading in the case of the single beam RF MEMS switch by analytically and numerically for piezo-electric actuation.
Displacement is linearly increased as the voltage increased. Larger displacement is obtained by applying a higher voltage for ANSYS and analytical simulation. The FEM and analytical simulation displacement for the single beam RF MEMS switch are very good agreement. Displacement investigation as a function of beam length, width are plotted shown in the figure 9 and figure 10 respectively using analytical and numerical (FEM ANSYS) solution by applying 2 voltage. It can be seen that single beam piezoelectric RF MEMS switch displacement will increase as the beam length and width increase.

It can be seen that, single beam piezoelectric RF MEMS switch displacement will increase as the beam length and width increase. From the figure 11 it is observed that the displacement is linearly decrease as the thickness of the piezoelectric layer increases for the case of ANSYS simulation. But in contrast of piezoelectric layer thickness, displacement decrease exponentially with the increasing piezoelectric layer thickness. This is because, thinner piezoelectric layer of RF MEMS switch needs more voltage for the displacement that is discussed in the analytical simulation. The possibility of this
reason is that, stress becomes increasingly important as the thickness of the piezoelectric film increases relative to the substrate layer.

![Graph showing displacement vs piezoelectric layer thickness](image)

**Figure 11.** Single beam RF MEMS switch analytical and numerical analysis comparison between displacement and piezo-electric layer thickness.

Single beam RF MEMS switch analytical and numerical analysis comparison for displacement have slight difference in the results. This can be attributed to the fact that, the analytical solutions are modelled by using isotropic material properties and the FEM model is based on anisotropic material properties. There is also one limitation that, the FEM model having a boundary condition where the analytical model do not have any boundary conditions.

5. **Conclusions**

The analytical model for the single beam RF MEMS switch is developed starting with the basic equations. Several assumptions are made in developing the analytical models that are best suited for behaviour of the single beam RF MEMS switches. Single beam type RF MEMS switches actuation voltage and contact force are analysed by the appropriate equations. Theoretical analysis of the design parameters are optimized for the minimum actuation voltage and high contact force. The optimized beam length and width of 2000 µm × 500 µm are obtained from the analytical analysis. Piezoelectric film thickness of 0.6 µm should be controlled at the smallest dimension considering the biggest electric gradient that the material can sustain. The optimized gap size and piezoelectric coefficient of 500 nm and 2.6 pm/V are obtained for the efficient and reliable operation of the switch. Using these methods, the parameter dependency of the different design characteristics are investigated. The optimized minimum actuation voltage and high contact force are less than 2 V and 100 µN respectively obtained by using the optimized analytical design parameters. The optimized design parameters are also used to simulate the FEM modelling of single beam RF MEMS switch. FEM models of the single beam RF MEMS switches are developed by using the optimized design parameters and presented to verify the analytical model. The results of the theoretical and numerical models are found to be in very good agreement.

In further investigations, bridge type RF MEMS switch need to design for analysis the nonlinear contact behaviours. For reliable operation of the RF MEMS switches, the FEM contact model need to investigate and contact part need to be optimized to maintain desirable contact force. This task will to be highly challenging and remarkable work in RF communication.
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