A modified capacitance model of shunt micro switch based on MEMS technology in actuation mode: simulation and analytical study

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Abstract: In this paper, a modified mathematical model for capacitance analysis of micro-electromechanical switch based on Agarwal’s Model has been presented. This model is applicable in the condition when the micro-switch is supplied with electrostatic voltages. Effects of perforated structure and fringe field are accounted for accurate capacitance analysis of the micro-switch. The switch parameters such as thickness of dielectric material and actuation voltage for micro switch have also been considered in the present study. The switch is designed and simulated using COMSOL Multiphysics tool and results obtained through simulations have been validated using MATLAB software. It is found that the results obtained by simulation and mathematical model are in agreement closely for the presented study. This model could be used for evaluation of capacitance in downstate of the micro-switch for symmetric structures.

1. Introduction

Advancement in Micro-electro-mechanical (MEMS) technology during last two decades has resulted in tremendous progress and replacement of FET components which were being used for various applications like switching devices [1-2], sensors [3-4], regulators [5], resonators [6], oscillators [7] etc. switches made during those days were available with certain limitations such as high power consumption, bulky in size, high losses and lack in performance for high frequency applications [8]. These limitations have been reduced and overcome using MEMS switch made up using micro fabrication technology [9,15]. These switches generally offer low loss in terms of return, insertion in on and have good isolation in off conditions. The performance associated with MEMS switches are represented in terms of associated loss and switching speed. The insertion loss, return loss and isolation are expressed in terms of capacitance in up and down condition [10]. Thus, there is a need to evaluate capacitance in these switches by considering the effects of fringe, holes and voltages properly so that a better estimation of the associated loss could be analysed and further improvement could be used for better performance. In the ref. [11], A model for calculation of pull in voltage of electrostatically actuated clamped type beam is presented on the basis of Meijs and Fokkema capacitance model in which softening and hardening effects due to fringe field capacitance and nonlinear beam deformation respectively have been utilised. But the limitation of this model is that the model is developed by considering that the fixed beam and transmission line ground is ideally plane before deformation. In ref. [12], up state capacitance of MEMS switch has been studied in terms of actuation voltage. The model uses non-uniform charge and capacitance distribution due to application of voltages. The investigations have been performed for stress gradient and stress time with increase and decrease in spring constant of the electrostatically actuated beam. The model somehow lacks in accurate prediction of capacitance on other parameters like dielectric used in switch and size of the beam used. In ref. [13],
a model for evaluation of capacitance in deformed condition of MEMS shunt switch is presented where capacitance analysis for different parameters of the switch such as thickness of the beam, change in spring constant, pull in voltage requirement is done along with RF performance of the switch. The model presented here does not accounts for effect of holes and fringing field for capacitance evaluation which may cause non-accurate results for RF performance and capacitance if used for a switch with holes. In ref. [14], a generalised capacitance model using Yang model is proposed where the effect of etched holes and fringe have been used to calculate the capacitance in undeformed and deformed conditions of the switch. The parameters for study were thickness of dielectric material, air gap height and size and shape of the holes made upon fixed beam. The model is applicable for non-uniform meander-based switches with square shaped holes. The model was validated by means of available other benchmark models. In ref. [15], the technique for improvement in actuation voltage and RF performance with circular perforations has been proposed and through the study it was observed that circular perforations result in better performance due to reduction in spring constant and scattering parameters of the transmission line. However, the study does not account capacitive analysis by consideration of holes.

In this article, we present capacitance analysis of clamped type MEMS micro-switch by consideration of effects of holes and fringe field with circular perforations for better analysis of the performance of the switch.

2. Switch Structure used in the Model

This section presents the design of micro switch which is based on MEMS working principle. In the MEMS switch the suspended electrode moves in inward direction on application of the electrostatic potentials to create OFF State. When no actuation potential is applied to the switch top electrode and bottom electrodes, the electrode remains untouched to the dielectric which prevents from capacitive short thus switch remains in ON state and allows the flow of signals from one end of transmission line to other end.

![Figure 1. Symmetric micro Capacitive Switch for study.](image)

The structure for the switch used in the present study is shown in Figure. 1 and Figure 2. The cross sectional view of the switch is represented in Figure. 1 whereas the top view demonstrating RF signal flow is represented in Figure. 2
Since we need to analyse the capacitance developed in the switch due to fringe and hole, we have created two structure of the switch keeping same switch dimensions. The first structure does not account holes whereas second structure is perforated to create hole on the top electrode [see Figure 3 and Figure 4]. The switch parameters used for the design is presented in Table.1.

| Sr. No. | Micro-switch Components          | Size (in µm) | Material used for study | Material’s Properties |
|--------|----------------------------------|--------------|-------------------------|-----------------------|
| 1      | Suspended Beam (Top Electrode)   | 100-5-1      | Gold (Au)               |                        |
| 2      | Transmission Signal line (Bottom Electrode) | 50-10-1 | Gold (Au)               |                        |
| 3      | Dielectric material thickness    | 0.4 -10      | Silicon Nitride (Si₃N₄) | Dielectric Constant – 9.5 |
| 4      | Gap B/w electrodes               | 0.6 (g₀)     | Air                     | Dielectric Constant – 1.0 |
| 5      | Ground                           | 20-10-1      | Gold (Au)               |                        |
| 6      | Substrate thickness              | 10 (r₁)      | Poly-silicon            |                        |
| 7      | No. of holes/ radius             | 62 hole/0.7 µm | -----                 |                        |
| 8      | Actuation Voltage                | 10.5 V for without hole | Electrostatic actuation method |

### 3. Mathematical Equations for Capacitance evaluation

The mathematical model in down state for the switch proposed in Section 2 can be obtained by using equations presented in ref. [16] and modified in ref. [17]. The total capacitance for down state comprises three terms: (a) Capacitance due to non-contact part of the switch ($C₁$) (b) capacitance due to contact...
part of the switch ($C_2$) and (c) capacitance due to holes for contact and non-contact part ($C_3$) which is demonstrated in Figure 5.

![Figure 5(a)](image1)

**Figure 5(a).** Demonstration of downstate capacitance on application of actuation voltage for micro switch.[13]

![Figure 5(b)](image2)

**Figure 5(b).** Demonstration of only non-contact part.[13]

To get the capacitance for non-contact part of the switch, we can use [16,17]

$$C_1 = 2 \times \frac{\varepsilon_r^2 \varepsilon_0 \cdot (1 - \beta) w}{t_d \cdot (g_0 - g_1)} \ln \left( \frac{\varepsilon_r + t_d \cdot (g_0 - g_1)}{\varepsilon_r} \right)$$

Where, $C_1$ is the capacitance due to non-contact part of the switch, $\varepsilon_r$ is the relative permittivity of the dielectric material, $\varepsilon_0$ is the permittivity of the free space, $g_0$ is the initial air gap between two electrodes, $g_1$ is the reduction in air gap due to application of actuation voltage ($g_1 < g_0$) and $(1 - \beta).w$ is the untouched segment of the half length of the signal line.

We can obtain the contact capacitance for the switch as

$$C_2 = 2 \times \frac{\varepsilon_0 \varepsilon_r \cdot w^2 (1 - \beta)}{t_d}$$

The equation for capacitance due to holes in ref. [16] missing one term for capacitance due to holes for non-contact part. The capacitance due to holes must have two components as capacitance due to holes for contact part and capacitance due to holes for non-contact part [17]

$$C_3 = \left( \frac{1.2834 \cdot n \cdot \varepsilon_0 \cdot A_0}{(g_0 + \frac{t_d}{\varepsilon_r})} \right) + \left( \frac{1.2834 \cdot n \cdot \varepsilon_0 \cdot \varepsilon_r \cdot A_0}{t_d} \right)$$

Where, $n$ is the no. of holes in the suspended bridge, $A_0$ is the overlapping area between suspended beam and transmission signal line.

The total capacitance in downstate position of the switch can be obtained as

$$C_t = (C_1 + C_2) + C_3$$

$$C_t = \left( 2 \cdot \frac{\varepsilon_r^2 \varepsilon_0 \cdot (1 - \beta) w}{t_d \cdot (g_0 - g_1)} \ln \left( \frac{\varepsilon_r + t_d \cdot (g_0 - g_1)}{\varepsilon_r} \right) \right) + \left( 2 \cdot \frac{\varepsilon_0 \varepsilon_r \cdot w^2 (1 - \beta)}{t_d} \right) + \left( \frac{1.2834 \cdot n \cdot \varepsilon_0 \cdot A_0}{(g_0 + \frac{t_d}{\varepsilon_r})} \right) + \left( \frac{1.2834 \cdot n \cdot \varepsilon_0 \cdot A_0}{t_d} \right)$$
\[
\left( \frac{1.2834 \cdot n \cdot \varepsilon_0 \varepsilon_r \cdot A_0}{\varepsilon_d} \right)
\]

The above expression is for capacitance evaluation of Shunt micro switch in down state condition considering effect of fringe and holes.

4. Results and Discussions

This section presents the result obtained through above presented model and discusses in detail. The micro switch results downstate capacitance in Pico farads. The two switch structures were designed using materials as per Table.1 and simulated using COMSOL Multiphysics tool and MATLAB was used for getting analytical result using above model.

![Figure 6. Actuated down state capacitance versus thickness of dielectric material.](image)

The thickness of dielectric material used is very important factor for monitoring change in capacitance. The effect of dielectric thickness on actuated capacitance is considered for the range of 0-10 µm [Figure 6]. The decrease in the capacitance for all three components is found for thickness of range of 0.4 to 1.5 µm and thereafter we can see there is a straight line for remaining values of dielectric thickness which implies that the dielectric thickness must be larger enough for a better capacitance ratio and it should not be very small such as 0.4 – 1.5 µm for presented structure of the switch. The individual effects of each component on total downstate capacitance can be seen and it can be observed that the effect of capacitance due to holes for contact and non-contact part is considered to be very important for evaluation of capacitance. The effect of fringe could also be observed in the above presented plot and it is also need to be considered while capacitance analysis in down state capacitance.

![Figure 7. Comparative result for capacitance without perforations, capacitance loss due to holes and capacitance considering fringe.](image)
The comparative results to see the effect of capacitance without having perforations, capacitance considering fringe field and capacitance loss due to holes is presented in Figure 7. From the Figure 7, it can be observed that fringe field have a great impact in capacitance evaluation and results in greater capacitance in down state which is very much desirable for high isolation in the switch. Capacitance without perforations generally have low capacitance compare to capacitance with fringe and holes, it should also be noted that holes create more fringe path with results in greater capacitance compare to small loss in capacitance due to holes.

![Figure 8. Effect of actuation voltage on down-state capacitance.](image)

The effect of change in down state capacitance of the switch on actuation voltage is demonstrated in Figure 8. It can be observed that the down state capacitance does not change up to a particular value of actuation voltage and remains unchanged. When actuation voltage crosses minimum actuation voltage level then the down state capacitance starts increasing exponentially. The simulated and analytical value of capacitance is presented in the graph. The sudden change in capacitance was observed after actuation voltage crosses 10.5 V which is clearly shown in the figure 8.

5. Conclusion

The MEMS switch RF performance is characterised by proper evaluation of capacitance in down state mode of the switch. In this article, we have used a modified model equation for evaluation of capacitance which is capable of calculating better capacitance and thus the performance of the switch could be evaluated with greater efficiency since it depends on capacitance of a micro switch. The model developed in this article is also capable of seeing the effect of individual capacitances on total capacitance on the application of actuation voltage. The model can also be used for evaluation of capacitance using different dielectric materials and suspended electrode materials to find out best down state capacitance value for high isolation of the switch. This article will be very useful for the authors working in the field of RF MEMS micro switch design and analysis.

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