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Analysis of Pull-in Behavior of Electrostatic MEMS Actuators for Optical Switching Applications

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Abstract: Micro Electromechanical Systems (MEMS) actuators experience pull-in instability in their actuation range. MEMS actuating elements are thin parallel plate capacitor electrodes separated with air gap. The electrodes are fabricated from silicon as substrate layer and gold /aluminum layer as functional layer for reflecting laser beam in optical switching application. When the top electrode is attracted towards bottom electrode, as it crosses one third distance of the gap between the electrodes, it undergoes pull-in/snap-down with bottom electrode. This condition severely limits the device operating range. These devices are operated either analog or digital mode for positioning of the top electrode. The plate electrodes actuated in tilting mode or bending mode and they are typically torsional structures or fixed-fixed structures. This paper provides theoretical pull-in analysis for the static behavior of a optical switch model. It is derived from analytical modeling of the parallel plate type with fixed-fixed structural end conditions. The effect of dielectric layer thickness is taken into account for predicting the pull-in voltage. During the piston mode actuation cycle, when the threshold (pull-in) voltage is reached, the switch is in the bent or ON state due to electrostatic repulsion/attraction and for the no voltage condition it is in the parallel or OFF state. The pull-in hysteresis behavior of the multilayered micro-actuator bending beam model is analyzed for the variation in thickness of dielectric material. In this paper, the critical role of different dielectric layer materials in bringing down the static pull-in voltage is discussed.

Key words: Micro electromechanical systems, thin parallel plate capacitor electrodes, micro-actuator bending, beam model, torsional

INTRODUCTION

The piston mode MEMS optical switch consists of a fixed-fixed type of deflectable top plate electrode and a bottom electrode insulated by a dielectric film, as shown in Fig. 1 and 2. The dielectric film primarily serves to avoid the electric short circuit between two conducting plate electrode surfaces. The pull-in voltage is decreased as the dielectric layer increases the force between the two electrodes (Saucedo-Flores *et al*., 2003).

When voltage is applied between the movable plate electrode and the fixed bottom electrode, electrostatic charges are induced on both the electrodes. Due to the electrostatic charges generated, electrostatic force actuates the movable micro plate electrode towards the bottom electrode. Due to the application of voltage, the bending deformation of parallel plate takes place. The deformed electrode stores the elastic energy which will restore the parallel state when voltage is removed.

In this paper for analysis of the piston mode type of actuation, electrostatic attraction forces towards bottom electrode is considered rather than electrostatic repulsion.

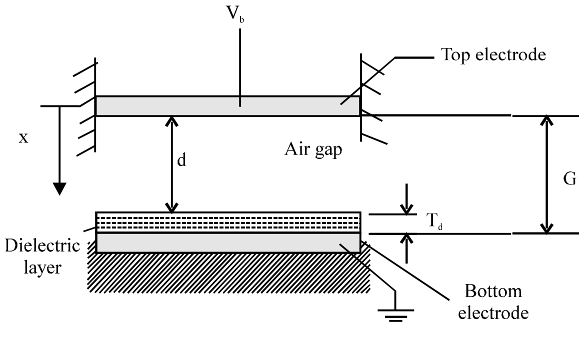

Fig. 1: The general structure of fixed-fixed plate electrodes for piston mode of actuation in optical switching applications

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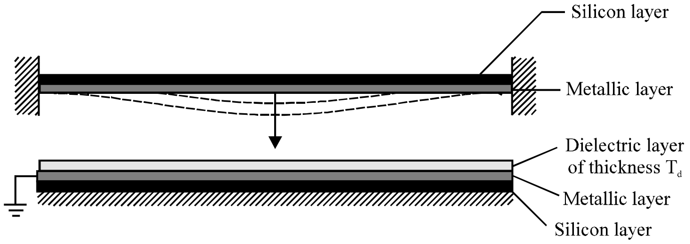

Fig. 2: The deflected state of top electrode in fixed-fixed structure as piston mode of actuation

Parallel-plate actuator is considered as a model of an electrostatic MEMS switch. Predicting the requirement of the driving voltage is critically important where the applicable voltage may be restricted to as in the case of electrostatic break-down phenomenon of isolation layers in the switching structure. The nonlinear and coupled electromechanical behavior is caused by structural deformation due to reorganization of all surface charges on the deformable electrode surface.

In fixed-fixed parallel plate structures, the axial stretching causes nonlinearity in stiffness and this effect is called as Duffing nonlinearity (Nielson and Barbastathis, 2006). This type of fixed-fixed switch models are considered as the good choice for Radio Frequency MEMS (RF MEMS) switches (He *et al*., 2009; Leus and Elata, 2008).

ANALYTICAL MODELLING

The MEMS switch is modeled as fixed-fixed beam of two parallel plates as shown in the Fig. 1. One plate is fixed electrode on the base substrate and the other formed by Au or Cu thin films on movable top electrode plate. Table 1 and 2 provide the numerical values of various geometric parameters and physical properties.

GEOMETRIC PARAMETER AND PHYSICAL PROPERTIES

The top electrode as shown in the Fig. 1 is deflected down by the force from its no-bias equilibrium position of displacement x as it remains there in a fully static state. This implies that the electrode speed and acceleration become null. The balanced forces are the externally applied force, the electrostatic force Ne between electrodes and the restoring spring force Ns associated to the flexible suspending features of the top plate and $\vec{u}$ is unit vector along +x axis, for the static model presented in the literature. The basic Eq. 1-6 presented in this paper are considered from Saucedo-Flores *et al.* (2003) and used for the calculation:

$$N_e + N_s = N_e - Kx\vec{u} = 0 \tag{1}$$

Table 1: The dielectric material and its dielectric constant value to be considered in analysis of hysteresis behavior of micro-actuator

Dielectric material	Dielectric constant
SiO_2	3.9
Si_3N_4	7

Table 2: The geometric and physical properties of the micro-actuator taken into considerations for the optical switch model

Parameter	Symbol	Value
Beam width	A	2 μm
Beam length	L	100 μm
Gap length	W	100 μm
Beam and gap thickness	T	2 μm
Initial gap	G	6 μm
Dielectric thickness	T_d	0.5 to 3 μm
Permittivity of air medium	ε_a	1 Farads/m
Permittivity of dielectric medium	ε_d	3.9
Relative permittivity	ε_0	8.85×10^{-12} Farads/m
Young's modulus	E	1×10^{11} GPa
Moment of inertia	I	$I = \frac{TA_3}{12}$
Area	A_p	A = W-T μm^2
Spring constant	K	$K = \frac{3EI}{L_3}$

Consider a parallel plate capacitor of area A_p with dielectric layer of thickness T_d. The electrostatic force magnitude is given by the equation:

$$N_e = \frac{\varepsilon_0 \varepsilon_a A_p V_b^2}{2(d-x)^2} \tag{2}$$

where, V_b is the applied bias and d is the geometric factor of the system which is defined by Eq. 1:

$$d = G - T_d \frac{1-C_a}{C_d} \tag{3}$$

where, G is the initial gap between the electrodes, T_d is the thickness of the dielectric layer in contact with the bottom electrode, ε_a and ε_d are the relative permittivity of air and the dielectric layer, respectively.

By substituting Eq. 2 in Eq. 1, we get:

$$K = \frac{\varepsilon_0 \varepsilon_a A_p V_b^2}{2(d-x)^2} \tag{4}$$

By re-arranging the Eq. 4 to solve for bias voltage (V_b), we get the voltage required to displace the top electrode for 'X' distance as follows:

$$V_b = \sqrt{\frac{2K}{\varepsilon_0 \varepsilon_a A_p} x (d-x)^2} \tag{5}$$

Now by differentiating Eq. 5 and equating to zero, solving for X, it has been found that the pull-in voltage, occurs at the following critical value of X:

$$X_{pull} = \frac{d}{3} = \frac{\left[G - T_d\left(1 - \varepsilon_a / \varepsilon_d\right)\right]}{3} \tag{6}$$

Now substituting Eq. 6 in Eq. 5, we get the expression for the pull-in voltage of the system:

$$X_{pull\text{-}in} = \sqrt{\frac{8Kd^3}{27\varepsilon_0 \varepsilon_a A_p}} \tag{7}$$

RESULTS AND DISCUSSION

In this study, the dielectric layers Silicon Dioxide and Silicon Nitride are considered in parallel plate micro-actuator. The changes in pull-in voltage are calculated for different dielectric layer thickness. The selection of minimum and maximum thickness of dielectric layer values based on the previous literature reports (Saucedo-Flores *et al*., 2003; Nielson and Barbastathis, 2006; He *et al*., 2009; Leus and Elata, 2008).

The effect of variation in the thickness of dielectric layer SiO_2 on the pull-in voltage is calculated shown in Table 3.

The variation of dielectric layer thickness which has an effect on the pull-in voltage is shown for SiO_2 material in Fig. 3.

The effect of SiO_2 dielectric layer thickness of 3 μm is compared with the effect of SiO_2 dielectric layer thickness of 0 μm. In this case the pull-in voltage of the system decreases by 49.77% when, the dielectric layer of material SiO_2 of thickness 3 μm is considered.

The effect of variation in the thickness of dielectric layer Si_3N_4 on the pull-in voltage is calculated shown in Table 4.

The effect of Si_3N_4 dielectric layer thickness of 3 μm is compared with the effect of SiO_2 dielectric layer thickness of 0 μm. In this case the pull-in voltage of the system decreases by 43.18% when, the dielectric layer of material Si_3N_4 of thickness 3 μm is considered.

The results presented by Saucedo-Flores *et al.* (2003) as shown in the Fig. 5. The details of the plate electrodes are given. The Area (A) = 28×28 μm^2 and the dielectric layer thickness t_d = 0.5 μm with a relative dielectric constant (B) ε_b = 3.9.

Table 3: The values of pull-in voltage and displacement of micro-actuator having dielectric layer material (SiO_2) of varying thicknesses

Dielectric layer thickness (μm)	Pull-in voltage (V)	Displacement (μm)
0.5	109.03	1.857
1.0	98.61	1.735
1.5	88.34	1.612
2.0	78.44	1.489
2.5	68.95	1.367
3.0	59.88	1.244

Table 4: The values of pull-in voltage and displacement of micro-actuator having dielectric layer material (Si_3N_4) of varying thicknesses

Dielectric layer thickness (μm)	Pull-in voltage (V)	Displacement (μm)
0.5	107.06	1.839
1.0	95.43	1.697
1.5	83.76	1.556
2.0	72.60	1.414
2.5	61.99	1.273
3.0	51.95	1.131

Table 5: Percentage of reduction in pull-in voltage for different dielectric layer's of same thickness

Dielectric material	Dielectric layer thickness (μm)	Pull-in voltage decreased (%)
SiO_2	3	49.77
Si_3N_4	3	43.18

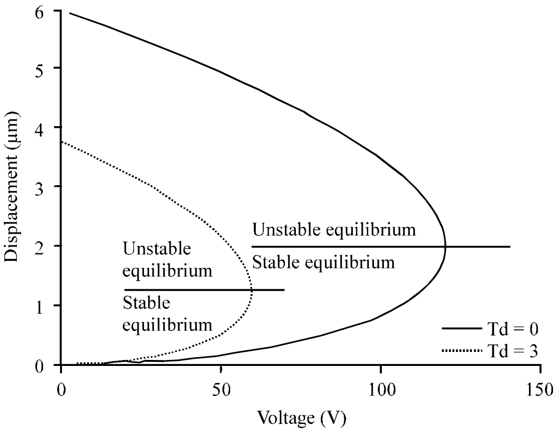

Fig. 3: Comparative study of pull-in voltage of micro-actuator with and without consideration of dielectric (SiO_2) layer

When dielectric layer thickness of the material SiO_2 and Si_3N_4 is increased, pull-in voltage and displacement parameters are decreased. The designer has to understand the trade off between power and actuation range. Table 3-5 values were listed from the graph values extracted from the Fig. 3 and 4.

The percentage of decrease in the pull-in voltage for the two different dielectric layers with same thickness is compared in Table 5. It was noted that SiO_2 shows more percentage of decrease in pull-in voltage in our calculation.

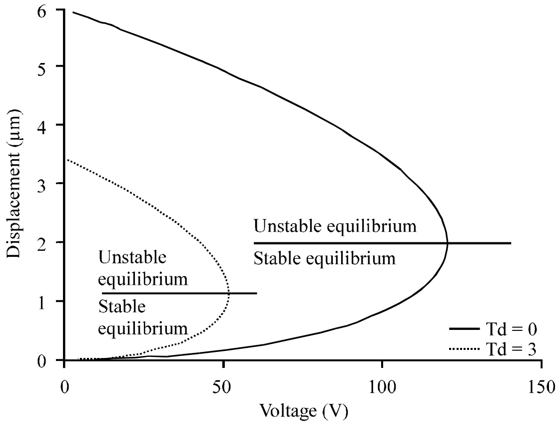

Fig. 4: Comparative study of pull-in voltage of micro-actuator with and without consideration of dielectric (Si_3N_4) layer

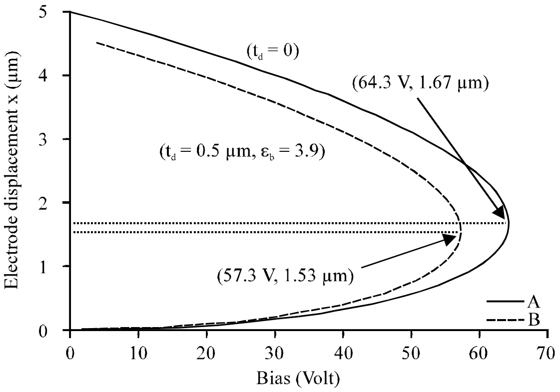

Fig. 5: Bias voltage vs. electrode displacement graph presented for comparison from Saucedo-Flores *et al.* (2003), A: Area, B: Dielectric constant

The presence of the inflection points of pull-in voltage and Pull-in displacement (Vpi, Xpi) on the curves shown in Fig. 3-5. They are represented as an infinite slope on the displacement and voltage non-linearity. These are associated to a physically stable condition. Beyond these inflection points, the upper branches of the curves present a negative slope (1).

CONCLUSION

This study showed the effect of dielectric layer in bringing down the pull-in voltage of the multilayered system for Silicon dioxide and Silicon Nitride dielectric materials considered.

The analytical equations for voltage bias V_b and the displacements are considered to get the required equation for pull-in voltage $V_{pull\text{-}in}$. MATLAB programming was used to analyze the effect of dielectric layer on micro-actuator graphically and also to solve the equations to get the values of pull-in voltage.

The stable electrode actuation range of the parallel plate model was also observed. This effect was analyzed by introducing the dielectric layer parameters coupled with geometric parameters on the basic electrostatic pull-in equations.

Their occurred the pull-in phenomena of the electrostatic MEMS actuator by lowering the pull-in voltage value. When, the dielectric layer SiO_2 with 3 μm was considered, the pull-in voltage decreased by 49.77%. It is more suitable for digital applications; as it favors the early onset of pull-in voltage limit.

The prediction of the behavior of the parallel plate micro actuators based on this approach will facilitate designers to select various parameter and influential factors within a wide range in their designs.

REFERENCES

He, X., Q. Wu, Y. Wang, M. Song and J. Yin, 2009. Numerical simulation and analysis of electrically actuated microbeam-based MEMS capacitive switch. Microsyst. Technol., 15: 301-307.

Leus, V. and D. Elata, 2008. On the dynamic response of electrostatic MEMS switches. J. Microelectromech. Syst., 17: 236-243.

Nielson, G.N. and G. Barbastathis, 2006. Dynamic pull-in of parallel-plate and torsional electrostatic MEMS actuators. J. Microelectromech. Syst., 15: 811-821.

Saucedo-Flores, E., R. Ruelas, M. Flores and J.C. Chiao, 2003. Study of the pull-in voltage for MEMS parallel plate capacitor actuators. Proceedings of the MRS Materialss society fall Meeting, December 1-5, 2003, Boston, pp: A5.86.1-A5.86.3.