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Design and Simulation of Mass-Spring-Dashpot System for RFMEMS Switch

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***Abstract*—Design and analysis the structure of the mass-spring-dashpot of the RFMEMS switch are presented in this work. Most familiar method applies in designing MEMS switch is the spring design with difference length and width. These two parameters affect the capability of the spring to support the mass during 'ON' and 'OFF' operation by applying Hooke's Law to identify a suitable spring constant. The analysis is to observe the effects of the electrostatic parameter in terms of voltage, pull in stability, transient rise time, harmonic mode related to the spring movement and von Mises stress of the design. The MEMS switch using this cantilever beam was 15.9375 V of pull-in voltage and transient time of 12 µs. The spring constant for this cantilever beam is 79.9 N with quality factor of 0.0158.**

***Index Terms*—RFMEMS, microswitch, electrostatic pull-in**

I. Introduction

At present, as the development in MEMS technology, Radio Frequency is one of the switch application and the fastest growing areas in commercial MEMS (Hao, 2001). Besides that, as we comparing RF MEMS switches to semiconductor switches, it is widely used in millimeter wave integrated circuits and microwave circuits. RF MEMS switch has a low insertion loss, good isolation, low return loss, high frequency, good Q-factor, and a low cost and power consumption. Therefore, this project is mainly on designing and simulating MEMS switch base on the latest technology.

There are two types of MEMS switches that can be developed, the series switch and the shunt switch. Shunt switches are famously developed by Chuck Goldsmith and his co-workers in 1995-2000 which known as Raytheon shunt switch or Texas Instrument Switch (Goldsmith et.al, 1996). Shunt switches are suitable designed for applications at 10-100 GHz. On the other hand, series switches are designed with a low ohm contact for the lower Gigahertz range which only used extensively for 0.1 to 40 GHz applications. It was designed in the late 1970s Petersen developed a new class of micromechanical membrane switch on silicon (Vijay et.al, 2002). Table 1 shows the previous design of shunt switch using difference material.

This work focused on designing the mass-spring which its dominant the residual stress on the support beams hence, "*I*" shape beam was chosen. It is important to get a lower spring constant to reduce the supply voltage beside lower the mechanical force to enable the mass touches the ground during 'ON' state. CoventorWare 2010 was used for simulation in terms of pull-in voltage, switching speed, and the resonant frequency.

TABLE I. Previous Design in RFMEMS Switch

Company/ University	Spring k_x (N)	Actuation Volt. (V)	Type	Fequenc y (GHz)
Chuck Goldsmith & Co-workers	6 – 20	30 – 50	Al	10 – 40
University of Michigan	1 – 10	6 – 20	Nickel	1 – 40
University of Michigan	20 – 60	12 – 25	Ti/Au	10 – 30
LG – Korea	4 – 10	8 – 15	Gold	1 - 10

II. Design Methodology

The spring-mass-dashpot system design is based on cantilever fixed-fixed beam consists of four spring structure which the model is stated in equation (1).

$$K = \frac{4Ewt^3}{l^3} \tag{1}$$

which K is spring constant, E is equal to 160 GPa is a silicon Young's Modulus, w is spring's width, l is spring's length t and is spring thickness. The mass-spring-dashpot system is illustrated in Figure 1. The spring constant will effects by the applied voltage. The pull-in occurs when the deformation exceeds the one third of the initial gap of the mass and ground. Thus, the key of analyzing electro-mechanics for MEMS devices is the study of the quasi-static pull-in properties.

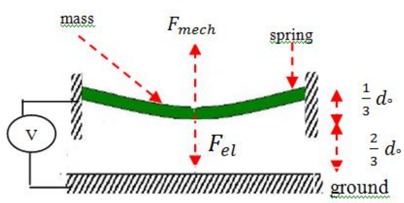

Fig. 1. Schematic diagram for fixed-fixed beam cantilever

The electrostatic force is given by (Yao, 2000):

$$F_{el} = \frac{\varepsilon\varepsilon_r A V^2}{2\delta_o{}^2} \quad (2)$$

which ε is the permittivity of the air, A is the area of the beam, V is the applied voltage and the δ_o is the initial gap. Meanwhile, the pull in voltage is given by (Rebeiz,2003):

$$V_{\text{pull-in}} = \sqrt{\frac{8K\delta_o^3}{27A\varepsilon_o}} \quad (3)$$

The damping coefficient for the spring can be calculated as:

$$b = \frac{3\mu A^2}{2\pi d_o^3} \quad (4)$$

which μ is the air viscosity that equal to 1.8x10^{-5} pA.s.

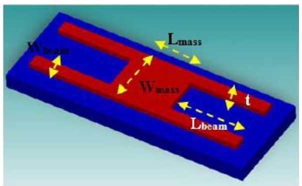

Fig. 2. RFMEMS switch microstructure

The Q factor can be easily controlled by adjusting the damping coefficient which relates the switching speed. Damping ratio is to determine the movement of spring and is given as:

$$\xi = \frac{b}{2m\omega_n} \quad (5)$$

The bandwidth, BW equation is given by:

$$BW = \frac{0.2 \times \omega_n}{2\pi} \quad (6)$$

TABLE II. PHYSICAL DIMENSION OF RFMEMS SWITCH

L_{mass}	200 µm	K	79.7 N
W_{mass}	200 µm	A_{beam}	4×10^{-8} m^2
t	3.65 µm	d_o	2 µm
L_{beam}	250 µm	V_{pi}	23.097 V
W_{beam}	40 µm	Q	0.0158
$mass$	3.65×10^{-10}	ξ	31.7
x	0.667 µm	P	133 Pa
ω_n	74.4 kHz	BW	2367.002 Hz

III. Result and Discussion

Design and simulation were carried out using CoventorWare 2010. Figure 2 shows the MEMS switch microstructure and the design parameters were summarized in Table 2.

TABLE III. COMPARISON OF MASS DISPLACEMENT WITH VARYING THE VOLTAGE BIAS.

V	Displacement (µm) – Theory	Displacement (µm) - Simulation
0	0	0
5	0.1443	0.03510
10	0.2886	0.1562
15	0.4329	0.4858
15.625	0.4509	0.5939
15.9375	0.4600	0.7059
23.1	0.6667	(Snap in)

The spring constant will affect the performance of MEMS switch in terms of beam deflection. By varying beam's length it's determined the difference of spring constant value and characteristic. For instance longer length of beam increased the spring constant and gave disadvantages which are lower the resonance frequency and bandwidth which against the needs for RF application. The spring design of the switch design has constant value of 79.7 N/m.

The electrostatic force was simulated to demonstrate the operation of the switch which applies the pull-in voltage effect. The electrostatic force becomes dominant over the linearly increasing mechanical restoring force and the beam quickly snaps to the ground plane. The pull-in voltage of 15.9375 V was defined from the simulation. The mass displacement as function of applied voltage was shown in Figure 3.

The simulation results listed in Table 3 proves theoretical calculation that the maximum displacement which is one third of initial gap is in approximately 0.6667 µm before the spring become unstable in two third regions from initial gap and contact to the ground. However, the difference of pull-in voltage is quite big which 15.93 V is a lower boundary while 16.25 V is an upper boundary for pull-in voltage. In order to obtain the exact pull-in voltage, the *CoSolve* iterations require more than the Maximum number of steps setting to achieve convergence.

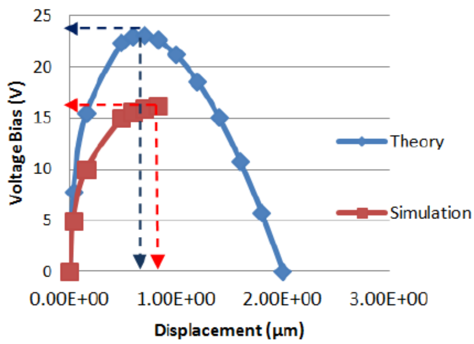

Fig. 3. Mass displacement as function of voltage bias

The deflection or mass displacement or RF microswitch was check by loading the mass and beams with distributed pressure or stress and later on it will show a maximum value of deflection. Pressure value was calculated and simulated in *MemMech* to gain the maximum displacement, in which resulting the plots shows in Figure 4. The value of 1330 Pa was a calculated value in which the deflection occurred in two third region of initial gap while 636 Pa was gained from simulation result. Thus the difference or error between simulated and theory result was found to be 52 %.

Von Misses stress distribution indicates a material is reaches its maximum limit before it damages due to yield stress. The criterion is crucial and important to indicate the survivability of the microstructure due to high pressure or shock impact. The material for the microstructure is silicon and it has yield stress between 2800 MPa to 6800 MPa. Figure 5 shows the von Misses stress distribution along the microstructure under distributed pressure loading condition.

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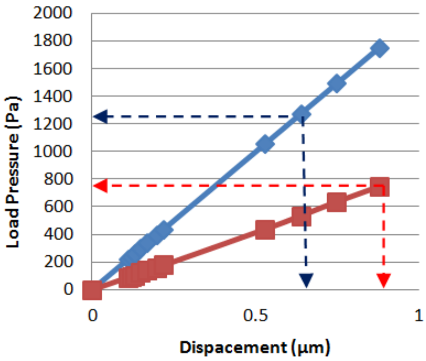

Fig. 4. Pressure as function of displacement for theory in blue line and simulation in red line.

The maximum stress is occurred at the end of each of the beams. Based on the result, the maximum von Mises stress of the beam is 17 MPa. Therefore it confirms that the design is survived based on the simulation value

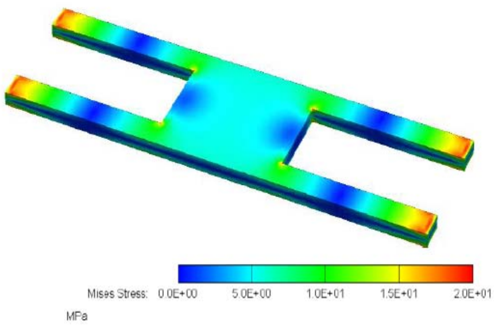

Fig. 5. Von Mises stress distribution with displacement of 0.7572 µm

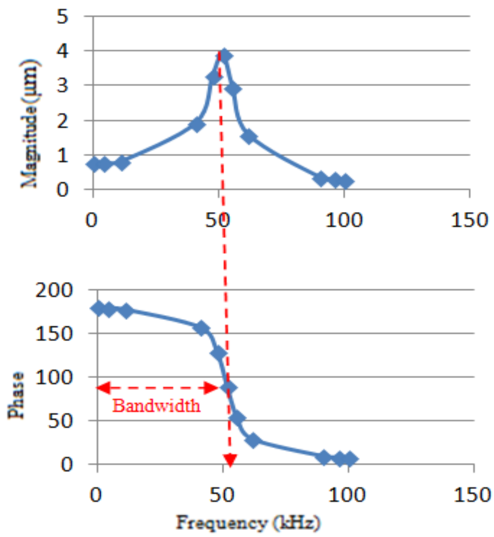

Fig. 6. Harmonic response consists of (a) magnitude in um and (b) phase as function of frequency in kHz

The structural response of fixed-fixed beam or harmonic analyses was observed when a harmonic pressure load is applied between in the range of frequency of 0.1 kHz and 100 kHz to the microstructure. Within the range of 0.1 kHz to 100 kHz, the modal able to produce 51.619 kHz as the peak frequency or resonance frequency for mode 1. The simulation results of harmonic response in terms of magnitude and phase were shown in Figure 6.

It is important to determine time required of a switch to move parts of the device from one position to another. The time required can be obtained by performing a transient analysis by loading electrical potential of 15.9375 V. The simulation result is shown in Figure 7.

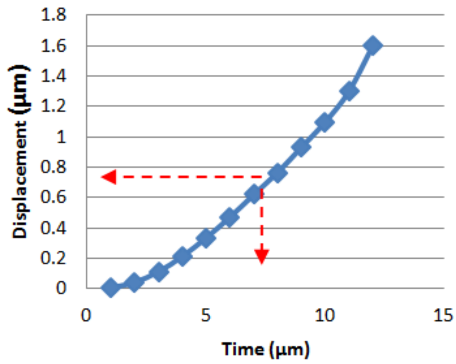

Fig. 7. Mass displacement as function of transient time.

The range of times interval between 1 µs and 10 µs were set up for transient time dependence. However, the simulation has stop time at 12 µs of 1.6 µm displacement. It shows that the beam become unstable at displacement of 1.6 µm and snap to the ground at 12 µs. As discussed earlier regarding to the pull-in voltage, the approximate displacement of the beam to contact the ground was 0.7 µm. The mass should be contacted to ground between time interval 7 µs and 8 µs. The switching time is considered relatively low for MEMS switch. Higher damping ratio leads to the slow transient time and response of the switch. Therefore in order to have a fast response in terms of rise time, damping ratio should be lower and trade off between spring design and Q factor need to be considered.

IV. Conclusion

You The mass-spring-dashpot system design was analysed and presented to design RFMEMS switch. The main design parameters consist of spring constant of 79.7 N and transient time or switching speed is 12 µs. The results between simulation and theory show deviation below 20%. The pull-in voltage of the design is between 15.9375 V and 16.25 V which is in the range of actuation voltage of 10V to 20V. Design optimization needs further adjustment in terms of trade off between spring design and damping factor in order to produce better switching speed.

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