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Radio Frequency-micro Electromechanical System Switch with High Speed and Low Actuated Voltage

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ABSTRACT

This paper presents a novel Radio Frequency-Micro Electromechanical System (RF-MEMS) fixed-fixed switch for very fast switching. Using the obtained equations, the switching time depends on the stiffness and effective mass of the switch beam so that the switching time will be decreased by higher stiffness (spring constant) and lower effective mass. In the new design, the suspension bridge is a three-layer beam so that the middle layer is aluminum and outer layers are alumina. The reduced dimensions and three layers of beam cause to increase stiffness and reduce the mass of the beam. This led to increase the resonant frequency and as a result, the switching time is reduced. The results show that, the switching time is 127 ns for the applied voltage of 27V and also the pull-in voltage is 18V. The return loss is 12 dB at the frequency of 60 GHz that is desirable and the achieved results is better than previous works. Therefore, this switch is suitable for high frequency applications.

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1. INTRODUCTION

For the past ten years, many efforts have been done in term of MEMS switches due to their advantages in high frequencies than the field effect transistors or PIN diodes. These advantages are low or close to zero power consumption, low cost, small in size and weight, high isolation, low loss, low return loss, high frequency, high quality factor, low intermodulation, wide bandwidth and high linearity [1-3]. But the MEMS switches have disadvantages such as low speed, low power handling, high actuated voltage, and low lifetime. The Micro-electromechanical switches can be used in high frequency circuits such as mobile phase shifters and smart antennas and low frequency circuits such as automatic test equipment (ATE), medical and industrial equipment [4-6].

MEMS switches consist of a thin suspension metal beam (bridge) over a fixed plate. MEMS switches are generally divided in two categories (ohmic, capacitance). They can be actuated using electrostatic, thermal, electromagnetic and thermal-electrostatic. But the capacitive switches with actuated electrostatic force are widely studied, because of their high insulation and low power consumption.

In this paper, a novel design of MEMS switch is presented to reduce the switching time. In the new design, the beam size is small to increase the stiffness of the bridge. The Young's modulus of the beam is increased using three-layer so that the middle layer is aluminum and outer layers are alumina. The reduced dimensions and three layers of beam cause to increase the stiffness and reduce the mass of the beam. This led to increase the resonant frequency and as result, the switching time is reduced.

2. RF MEMS CAPACITIVE SWITCHES

The RF MEMS capacitive switch consists of two electrodes, the bottom electrode is the central transmission line of coplanar waveguide and the upper electrode is a thin metal beam which is suspended on the lower electrode (see Figure 1) [7]. The applied bias voltage makes the electrostatic force, that the bridge is down on the signal line and large capacitance is formed which the ac signal is shortened to the ground. Thus the

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switch is in off mode. A dielectric layer is placed on the signal line to prevent the contact of metal bridge and signal line.

2. 1. Pull-in Voltage When a voltage is applied between two plates, moveable plate by electrostatic force is moving down to the fixed plate. Figure 2 shows an approximate model of a shunt capacitor that the upper plate is suspended by an ideal spring. This model is very simple and intuitive here to find a better understanding of the structure and design parameters.

The spring constant of fixed-fixed switch represents the stiffness of the material and depends on the Young's modulus and inertia that its value is obtained from the following equation [8]:

$$K=4Ew\left(\frac{t}{l}\right)^3 \tag{1}$$

Where, E is the Young's modulus, t is thickness, w is width and L is the length of the beam. The capacitor is formed between beam and bottom electrode and is given by:

$$C=\varepsilon_0\frac{A}{g}=\varepsilon_0\frac{Ww}{g} \tag{2}$$

where w is the beam width, W is the width of bottom electrode, ε_0 is Electric permittivity of air and g is the distance between the beam and the lower electrode under applied voltage that is called air gap. The electrostatic force, F_e, between beam and bottom electrode can be calculated as follows:

$$F_e=\frac{1}{2}v^2\frac{dc}{dg}=-\frac{1}{2}\varepsilon_0\frac{Wwv^2}{g^2} \tag{3}$$

where v is the applied voltage. The electrostatic force is applied uniformly on the surface of the beam. Therefore, the displacement of the beam can be calculated using Equation (1). It is should be noted that the spring constant of the movements performed in the place of force should be considered. By equating the electrostatic force and spring force, $F=k(g_0-g)$, at equilibrium, the actuation voltage is obtained [9]:

$$V=\sqrt{\frac{2kg^2(g_0-g)}{\varepsilon_0 Ww}} \tag{4}$$

where g_0 is the distance between the beam and the lower electrode in zero bias. When the applied voltage is increased, electrostatic force increases. At distance of $^2/_3 g_0$, the electrostatic force is greater than the spring force and thus the beam collapses suddenly on the bottom electrode. As a result, according to Equation (2), the capacitance is increased by decreasing the separation between the plates. Using Equation (4) the pull-in voltage, V_p, is obtained as follows [9]:

$$V\left(\frac{2}{3}g_0\right)=\sqrt{\frac{8Kg_0^3}{27\varepsilon_0 Ww}}V_p \tag{5}$$

2. 2. Switching Time The time it takes to movable beam arrive to fixed electrode is called the switching time that by the displacement equation of beam is obtained. The dynamic equation of motion of the beam is:

$$m\frac{d^2}{dt^2}+kz=F_e=\frac{1}{2}\frac{\varepsilon_0 wWV^2}{g^2} \tag{6}$$

where m is the effective mass of the beam and Z is the displacement from up-state. Initial conditions of Z and dz / dt at t = 0 is zero and switching time for $Z = g$ by solving the differential equations of motion beam are obtained as follows [5]:

$$t_s=3.67\frac{V_p}{\omega_0 V_s} \tag{7}$$

where $\omega_0=\sqrt{\frac{k}{m}}$ is the resonant frequency, V_s is supply voltage and V_p is the pull-in voltage. From Figure 3, it can be seen that the switching time is reduced by increasing of V_s. But excessive V_s causes the system to be instable and unreliable. So in most cases, V_s is 1.5 times of V_p.

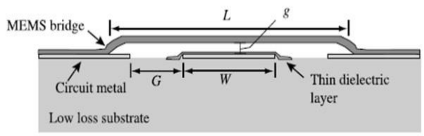

Figure 1. Capacitive switch on the coplanar waveguide (CPW)

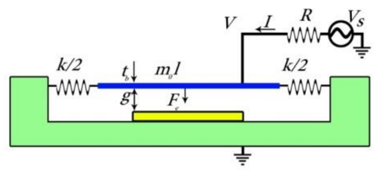

Figure 2. Spring model of a switch

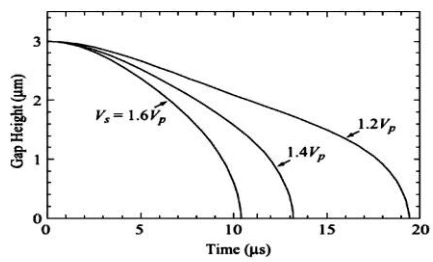

Figure 3. Switching time vs. applied voltage

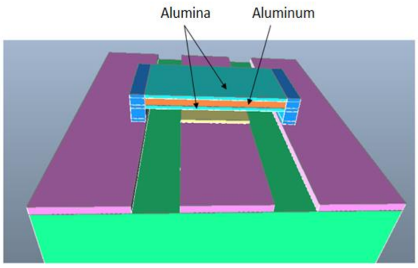

Figure 4. Capacitive RF-MEMS switch with three-layers of beam

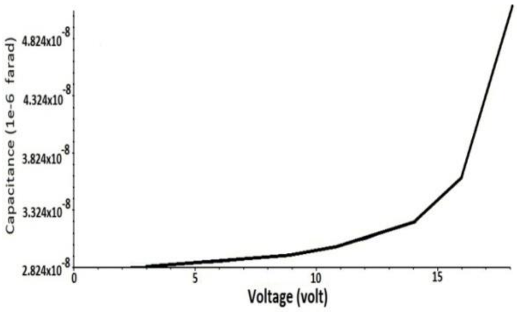

Figure 5. Capacitance versus applied voltage

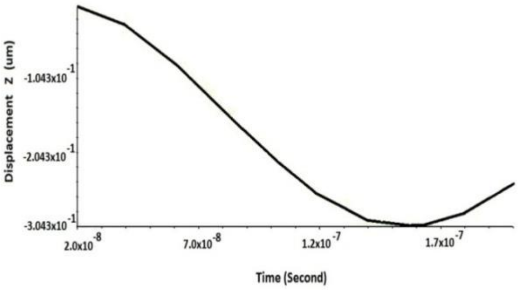

Figure 6. Switching time for applied voltage of 27V

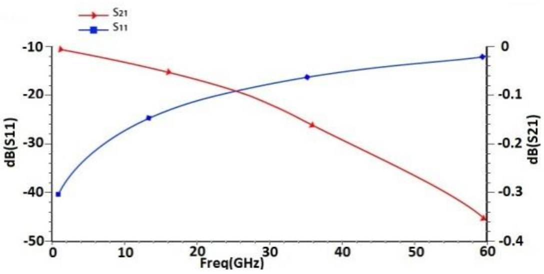

Figure 7. Return and insertion losses of switch without applied voltage

3. DESIGN OF NEW MEMS SWITCH

The switching time is only dependent on the resonant frequency while this frequency is related to the effective mass and the coefficient of beam stiffness. Therefore, the beam must be both stiff and light. As a result, several parameters can be adjusted: the beam dimensions (particularly beam length), beam structural material regarding its density and Young's modulus.

For the presented design, a fixed-fixed beam is used due to its higher stiffness capabilities than cantilever geometry. Aluminum material has been preferred to gold to realize the movable structure, since a stiff and light beam is sought. Indeed, the gold density is 19.3g/cm^3 whereas aluminum one is 2.7 g/cm^3 for a similar Young modulus (78 GPa for gold and 70 GPa for aluminum). Moreover, it was necessary to enhance significantly the aluminum beam stiffness with no significant mass increase in order to push the intrinsic beam mechanical resonant frequency up to several MHz. Hence, we have looked for stacking aluminum layer between two layers of a stiff and light material. Alumina is particularly a good candidate. Thanks to its low density of 3.9 g/cm^3 and its strong Young modulus of 380 GPa. Finally, the movable beam is made with a 100 nm thick aluminum core layer sandwiched between two 100 nm thick alumina layers.

Figure 4 shows the new RF MEMS capacitive switch structure. Length and width of beam is 35µm and 25µm respectively, and the width of bottom electrode is 15µm. High stiffness also results high pull-in voltage. As a result, to keep moderate pull-in voltage, the gap between the actuation electrode and the suspended beam was fixed to 300 nm. The advantage of reducing the size is to improve the mechanical behavior by increasing the spring constant and the restoring force per contact area.

4. RESULTS AND DISCUSSION

When a voltage is applied to the electrode, by increasing the electrostatic force, upper electrode moves toward the lower electrode. So that the capacitance increases between the electrodes as far as the top electrode once collapses on the bottom electrode. The collapse voltage is called pull-in voltage. Figure 5 shows a diagram of capacitance versus applied voltage. It can be seen that the average pull-in voltage is 18V.

The switching time is obtained using IntelliSuite MEMS simulation tool. Figure 6 shows the switching time. It can be seen that for applied voltage of 27v (1.5 V_p) the switching time is 127 ns. For more applied voltages, less switching time can be achieved. But the applied voltage for stability of switch is 1.5 times of pull-in voltage (1.5V_p).

We used HFSS three-dimensional software for analysis of insertion and return losses. The software calculates the scattering parameters of a structure by solving Maxwell's equations with respect to all losses, including conductor, dielectric and radiation losses etc. First, we consider the switch structure without applying voltage (off mode). Figure 7 shows the S-parameters of switch using HFSS software (return loss, S11, and insertion loss, S21).

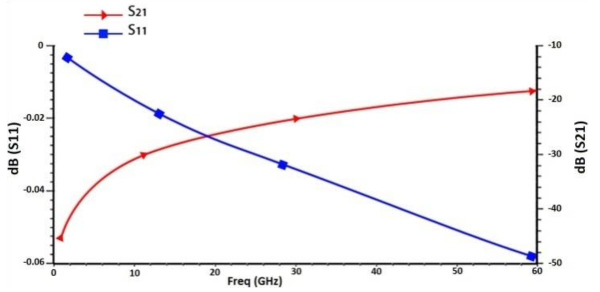

Figure 8. Isolation and return loss

It can be seen that the return loss is better than 12 dB at frequency of 60 GHz, which is desirable and insertion losses up to 60 GHz frequency is less than 0.36 dB, which is useful. Thus, the switch can also be used at high frequencies. Figure 8 shows the isolation and return loss when the switch is ON (down position). It can be seen that the isolation is much better than 18 dB up to 60 GHz frequency, which is also desirable. The return loss is less than 0.06 dB up to frequency of 60 GHz, which is suitable.

5. CONCLUSION

This paper presents a new mechanical design devoted to fast switching speed RF MEMS capacitive components. From three layers beam with miniature geometry, switching speeds as fast as 127 ns have been obtained under 27 V and also the pull-in voltage is 18V that is better than the previous works. HFSS software was used to analyze high frequency. The return loss is better than 12 dB at frequencies of 60 GHz that is desirable. Thus, this switch is suitable for high frequency applications, where the switching speed is very important.

6. REFERENCES

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چکیده

این مقاله یک سوئیچ جدید RF MEMS دو طرف ثابت برای کار در سرعت بالا معرفی می نماید. با استفاده از معادلات و روابط به دست آمده، زمان سوئیچینگ به سختی پل و جرم موثر بیم بستگی دارد به طوری که هرچه سختی پل بیشتر و جرم موثر بیم کمتر باشد زمان سوئیچینگ کمتر خواهد شد. در طرح جدید از بیم سه لایه در پل معلق استفاده شده است به طوری که لایه وسط از جنس آلومینیوم و لایه های کناری از جنس اکسید آلومینیوم می باشد. کاهش ابعاد و استفاده از بیم سه لایه باعث شده است سختی بیم افزایش و جرم بیم کاهش یابد. این کار باعث افزایش فرکانس رزونانس و در نتیجه کاهش زمان سوئیچینگ شده است. نتایج نشان می دهد زمان سوئیچینگ به ازای ولتاژ اعمالی ۲۷ ولت ، ۱۲۷ نانو ثانیه و ولتاژ راه اندازی سوئیچ نیز ۱۸ ولت می باشد. تلفات بازگشتی تا فرکانس ۶۰ گیگاهرتز مقداری بهتر از ۱۲ دسی بل را دارد که مطلوب می باشد و نتایج بهتری نسبت به کارهای قبلی حاصل شده است. بنابراین این سوئیچ مناسب برای کار در فرکانس های بالا می باشد.

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