DC-contact radio-frequency microelectromechanical system symmetric toggle switch on a borofloat substrate

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Published in Micro & Nano Letters; Received on 25th January 2013; Revised on 26th February 2013; Accepted on 1st March 2013

Presented is a DC-contact radio-frequency (RF) microelectromechanical system symmetric toggle switch for broadband power applications. Based on the lever principle, the proposed switching structure can be toggled upwards with extra restoring force using push electrodes. This push mechanism greatly improves the isolation and efficiently avoids the down-state stiction of the contacts which leads to enhancement of the power-handling capability. The measured actuated voltage is 33.4 V and the contact resistance of the switch can be further decreased to 0.18 Ω under a pull in voltage of 60 V, which results in the improvement of insertion loss. The switch can be properly restored with a voltage of 30 V applied to the push electrode. In addition, the substrate loss is reduced by using a Boroloat™ glass substrate. The RF measurement results show that the switch can handle a minimum 1 W incident RF signal power with isolation and an insertion loss of better than −30 and −0.24 dB from DC to the X-band.

1. Introduction: The performance of the radio-frequency microelectromechanical system (RF MEMS) switch has been significantly improved over the last decade. Compared with conventional solid-state RF switches based on P–intrinsic–N-type diodes or field effect transistors, MEMS switches exhibit superior properties in terms of insertion loss, isolation, linearity and power consumption [1]. However, MEMS switch designers still face challenges with respect to power-handling ability and reliability, which seriously limit the potential of MEMS switches in many applications. To improve the power handling of MEMS devices, thick metal plates and large dimensions of both the coplanar waveguide (CPW) and MEMS bridges are considered in the switch designs [2–5]. However, these methods increase the difficulty and cost of fabrication. In 2005, an MEMS capacitive shunt switch with a symmetric toggle structure was first introduced by Rangra *et al.* [6]. In comparison with conventional MEMS switches with a doubly clamped beam or cantilever structure, the toggle switch can achieve extra restoring force for the top electrode from the push electrodes based on the lever principle, which leads to higher isolation, larger power-handling capability and greater reliability. Furthermore, the symmetric configuration improves the mechanical and electrical characteristics of the switch. In 2010, Solazzi *et al.* [7] designed and manufactured an active push/pull toggle RF MEMS capacitive shunt switch with a similar symmetric structure. Long-term stress characterisation of the switch has been performed, proving the lifetime of the device for over 50 million cycles. However, there is no DC-contact switch using this symmetric toggle structure as far as we know.

In fact, the toggle structure is especially useful in a DC-contact switch. Although a capacitive shunt RF MEMS switch performs well at higher frequencies, its isolation loss is worse at lower frequencies [8]. The DC-contact RF MEMS switch has a better insertion loss because of the small contact resistance of the metal to metal contact. When the switch is not biased, the RF signal is disconnected. Therefore the level of isolation of the switch is high and can be used well at lower frequencies as a complement to the capacitive switch. However, DC-contact switches suffer from two stiction problems. Besides the stiction between the top and bottom electrodes caused by surface tension or intermolecular forces [9], the top electrode can easily adhere to the bumped contact points of the signal line in high-current designs because of microwelding and material transfer around the contact area [10]. To reduce the down-state stick force and enhance the power handling ability of the DC-contact RF MEMS switch, a novel high-performance DC-contact symmetric toggle RF MEMS switch was designed, fabricated and characterised. From DC to 30 GHz, the insertion loss and the isolation of the switch were better than −0.46 and −24 dB.

2. Switch design: The structure and equivalent circuit of the symmetric toggle DC-contact switch are shown in Figs. 1 and 2. The switch consists of a movable gold top electrode that is mechanically anchored by four torsion beams. Three bottom electrodes are used to toggle the switch between the on and off states. The bottom electrode between the input and output CPW signal lines (s-lines) is the pull electrode, whereas a couple of bottom electrodes placed on the outer side of the torsion springs are push electrodes. When the pull electrode is biased by a voltage, the middle part of the top electrode will be pulled down and contact the s-line, which corresponds to the on-state of the switch. In this situation, the contacts can be equivalent to two series contact resistances, as shown in Fig. 2*a*. In contrast, when a voltage is applied to the push electrodes, the middle part of the top electrode will move upwards because of the lever push–pull mechanism, making the s-line an open circuit, which indicates the off-state. The equivalent series coupling capacitances between the top electrode and the s-line, which determine the isolation, are shown in Fig. 2*b*. The push–pull mechanism in this situation significantly improves the isolation by decreasing the off-state coupling capacitance, and provides the middle part of the top electrode with an active restoring force. The increased restoring force can substantially reduce the possibility of adhesion between the middle parts of the top and pull electrodes, which is caused primarily by surface tension and van Der Waals force. Furthermore, when in the hot switching condition, as the metal contacts first separate, they are very close to each other and arcing will occur because of the direct field emission, and leads to contact stiction [10]. The increased restoring force decreases the probability of micromelting and to some extent improves the switch power capacity. The equivalent elastic coefficient of the middle part of the top electrode can be found from the deflection

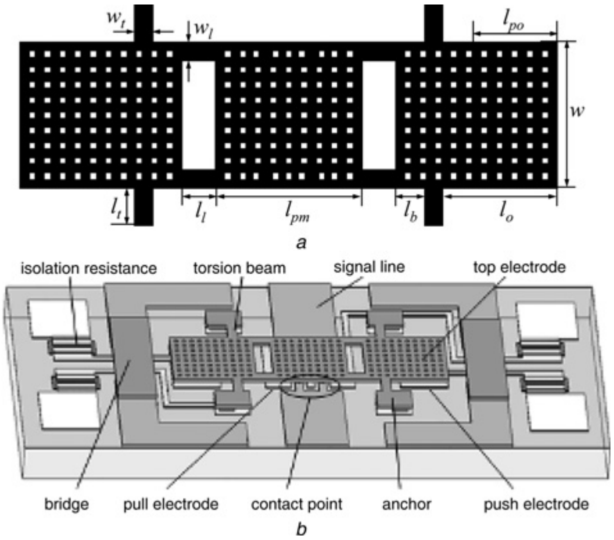

Figure 1 *Schematic diagram of the symmetric toggle switch*
a Top electrode of the switch
b Three-dimensional structure of the switch

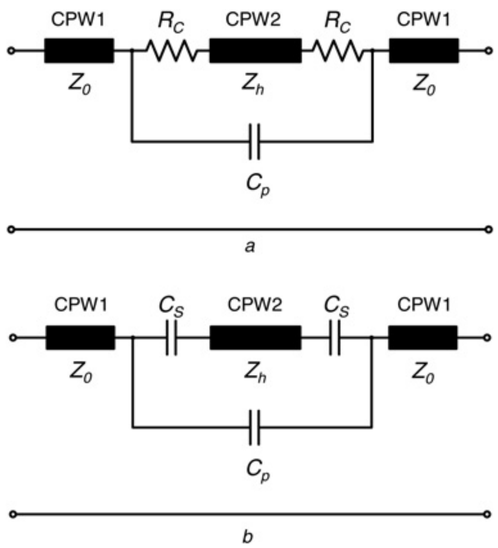

Figure 2 *Equivalent circuit of the switch*
a For the on-state
b For the off-state

against load position [11] and is given by

$$k_m = 32Ew\left(\frac{t}{l}\right)^3 \times \frac{1}{16(x/l)^4 - 64(x/l)^3 + 72(x/l)^2 - 16(x/l) - 3} \quad (1)$$

where $l = l_{pm} + 2l_l + 2l_b + w_t$ and $x = l_{pm} + l_l + l_b + w_t/2$. The size parameters l_{pm}, l_l, l_b and w_t are all marked out in Fig. 1.

When the middle part of the top electrode is in the downstate and a voltage V is applied to the push electrodes, the moment acting on the outer part of top electrode is

$$M_o = \int_{l_2}^{l_3} \frac{1}{2} \frac{\varepsilon_0 w V^2}{[(l/l_1)g_0]^2}(l - l_1)\,dl = \frac{\varepsilon_0 w V^2 l_1^2}{2g_0^2}\left(\ln\frac{l_3}{l_2} + \frac{l_1}{l_3} - \frac{l_1}{l_2}\right) \quad (2)$$

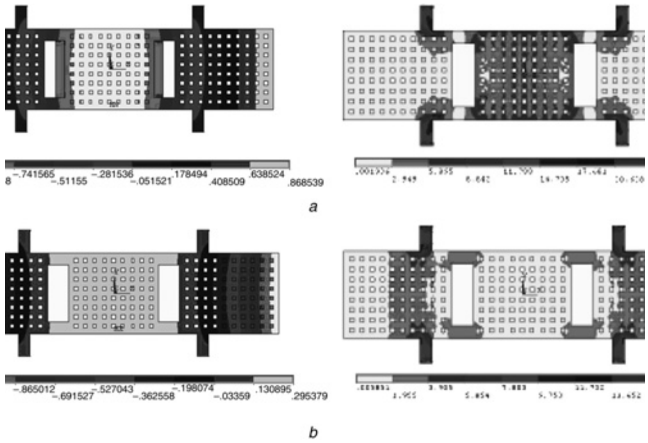

Figure 3 *Deformation and stress intensity of the toggle structure*
a 20 V voltage is applied between the top and pull electrodes
b 20 V voltage is applied between the top and push electrodes

where g_0 is the distance between the top and bottom electrodes, $l_1 = l_l + l_b + w_t/2$, $l_2 = l_l + l_b + w_t + l_o - l_{po}$ and $l_3 = l_2 + l_{po}$. In addition, l_o and l_{po} are marked out in Fig. 1, and l_{po} is the length of the push electrode.

Using the lever principle, the middle part of the top electrode can obtain an extra restoring force F_t, which can be described as

$$F_t = \frac{\varepsilon_0 w l_1 V^2}{g_0^2}\left(\ln\frac{l_3}{l_2} + \frac{l_1}{l_3} - \frac{l_1}{l_2}\right) \quad (3)$$

Therefore the total restoring force of the top electrode will be

$$F_{up} = k_m g_0 + F_t \quad (4)$$

The dimensions of the designed symmetric toggle RF MEMS switch are: $l = 380$ μm, $w = 190$ μm, $x = 300$ μm and $W = 190$ μm. The overlap area and the initial gap between the top and pull electrodes is $A = 320$ μm × 190 μm and $g_0 = 3$ μm. Through calculation, the equivalent elastic coefficient that causes the middle part of the top electrode to move downwards is $k_m = 35.4$ N/m, and the relevant pull-down voltage is $V_{pull\text{-}down} = 22.9$ V. When a voltage of $V = 60$ V is applied to the two push electrodes, an extra restoring force of 19.7 μN can be gained because of the lever principle. This extra force is approximately 20% greater than that of the switches with a conventional structure.

The symmetric toggle RF MEMS switch was simulated using the Ansys software. When a 20 V voltage was applied between the top and pull electrodes, the top electrode moved downwards. On the other hand, when a 20 V voltage was added between the top and push electrodes, the middle part of the top electrode was levered upwards. The distribution of the deformation and the stress intensity are shown in Fig. 3. The simulation results show that the toggle structure can achieve the designed push–pull effect. As shown in Fig. 3, the stress is mainly concentrated on the torsion beams, which means the torsion beams are key parts in the symmetric lever movements.

3. Measurement results: The micrograph of the switch is shown in Fig. 4. The switch was fabricated on a low-loss Borofloat™ glass substrate and Au was used as the material of the CPW and top electrode to improve the RF performance of the switch. The sacrificial layer was made from ZKPI-306 type polyimide [12] and was etched away in the last step of the fabrication process. The tested pull-in voltage was 33.4 V. The large drift from the calculated and simulated values is because of the unexpected high deformation gradient, which leads to an out-of-plane displacement of the top electrode. To achieve a better RF performance, an

Micro & Nano Letters, 2013, Vol. 8, Iss. 5, pp. 221–224
doi: 10.1049/mnl.2013.0044

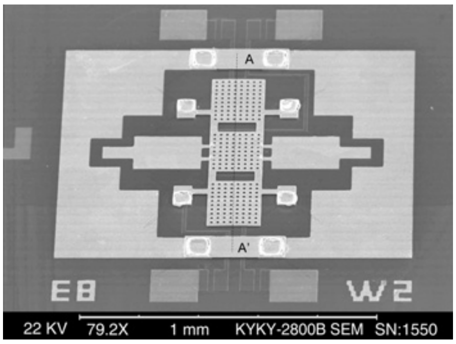

Figure 4 *Micrograph of the manufactured DC-contact RF MEMS symmetric toggle switch*

actuated voltage of 60 V was needed. The push–pull mechanism of the lever was investigated using an optical surface profiler. The curves achieved by scanning along the *AA′* direction in Fig. 4 are shown in Fig. 5. When a voltage of 60 V was applied to the pull electrode, the middle part of the top electrode completely collapsed and the outer parts of the top electrode were toggled up, as shown in Fig. 5*a*. When a voltage of 30 V was applied to the push electrodes, the outer parts of the top electrode moved downwards and the middle part of the top electrode was levered up to form an arch, as shown in Fig. 5*b*. To prevent the middle part of the top electrode from being dragged down by the outer parts, the voltage imposed on the push electrodes cannot exceed 30 V.

The RF performance of the switch was tested using an HP8722ES vector network analyser and the measurement results are shown in Fig. 6. In the frequency range from DC to 30 GHz, the isolation and the insertion loss are better than −24 and −0.46 dB. The insertion loss increases significantly after 30 GHz because the long top electrode introduces large parasitic effects which significantly affect the performance of the switch in the higher-frequency band. The recommended frequency range of the switch is from DC to the X-band where the isolation and insertion loss are better than −30 dB at 12 GHz and −0.24 dB at 12 GHz.

The switching time was measured using the dynamic response system Keyence LC-2400A. The laser generator and the displacement sensor are core-blocks of the whole system and the accuracy of measurement can reach 0.01 μm. The switching time of the proposed switch was about 60 μs, as the pull down and rebound time are all approximately 30 μs. A simple cantilever switch, which was fabricated along with the symmetric toggle switch, was also

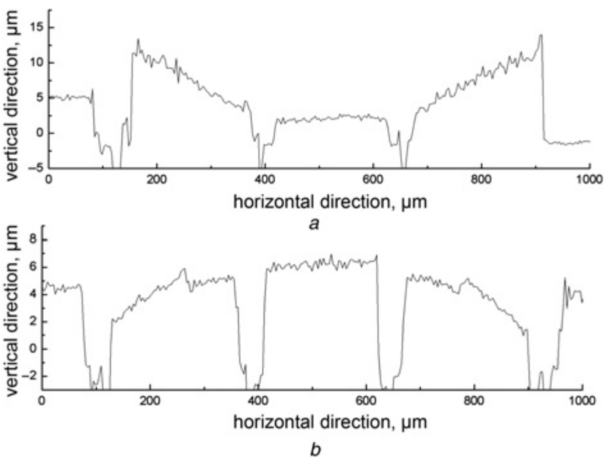

Figure 5 *Vertical displacement of the top electrode along the AA′ direction in Fig. 4*
a Voltage of 60 V is applied to the pull electrode
b Voltage of 30 V is applied to the push electrodes

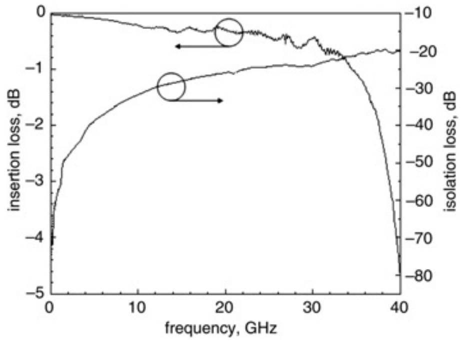

Figure 6 *Tested S parameter of the RF MEMS switch*

measured in the same system. The switching time of the simple cantilever switch was about 80 μs, because the rebound time was a little longer than for the symmetric toggle switch.

The power-handling ability of the switch was also tested in the RF testing system at 10 GHz. The switch worked well in the RF testing system. Unfortunately, the testing system we used could only provide an RF signal power up to 1 W. However, we were able to establish that the switch can withstand at least 1 W RF power.

Using the curve-fitting method, the resistance, capacitance and inductance parameters of the equivalent circuit can be obtained from the experiment results. The one-side contact resistance R_C was only 0.18 Ω for the on-state of the switch, and the coupling capacitance C_S between the top electrode and the s-line was as small as 7 fF for the off-state of the switch.

Other device characteristics such as temperature stability and lifetime are yet to be measured, but there are clear reasons to expect this type of device to perform well in these areas.

4. Conclusions: To improve the power handling capability and reliability of the RF MEMS DC-contact switch, a novel symmetric toggle structure was used in the switch design. The push–pull mechanism of the switch structure efficiently prevents the down-state stiction of the switch and enhances the power handling capability. The fabricated switch exhibits low insertion loss and high isolation, which are better than − 0.46 and − 24 dB, from DC to 30 GHz. The recommended frequency range of the switch is from DC to the X-band where the isolation and insertion loss are better than − 30 and − 0.24 dB, and the power handling of the switch is above 1 W.

5. Acknowledgments: This work was funded by the National Sciences Foundation of China (NSFC) with contract no. 91023040 and is supported by the Tsinghua Nanofabrication Technology Center.

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doi: 10.1049/mnl.2013.0044