Mechanically tri-stable, true single-pole-double-throw (SPDT) switches

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Received 2 June 2006, in final form 28 July 2006
Published DD MMM 2006
Online at stacks.iop.org/JMM/16/1

Abstract
This paper reports on a mechanically tri-stable switch mechanism based on laterally moving electrostatic curved-electrode actuators. The switch is configured in a ‘true’ single-pole-double-throw configuration (SPDT), i.e. a single-switch mechanism allows for the input signal to be switched between two output ports. The switch has three stable states: (1) input to first output; (2) switch off; (3) input to second output. Because of a latching mechanism, these states are mechanically stable, i.e. they are maintained without applying external actuation energy. The fabrication of the switches is done by a single photolithographical step and deep etching of a silicon-on-glass wafer which is subsequently coated with sputtered gold. The switch design features active opening, and the contact force is created passively by the deflected cantilevers. The curved-electrode actuators are utilized close to their end position where they develop their maximum force to guarantee a very large opening force which makes the switch less susceptible for contact stiction. The actuation voltages for different designs and functions of the switches are between 30 and 85 V.

1. Introduction

1.1. Single-pole-double-throw switches

Since the first characterization of a micromachined switch was presented in 1991 [1], MEMS micro-switches have attracted a lot of attention because of their superior signal handling properties as compared to solid-state relays and macroscopic, electromagnetic relays [2–5]. The near-ideal signal handling properties of metal-contact micro-switches stem from the pure mechanical switching nature of the gold contacts, which results in high isolation, low insertion loss and excellent signal linearity. Because of their small size they are low intrusive to the signal line, which has proved to extend the bandwidth of their good signal properties from dc to as high as 40 GHz [6]. Another main advantage of MEMS switches is the almost-zero power consumption for electrostatic actuation mechanisms, which are the most commonly used principle.

In its very basic function, a switch interrupts or allows the propagation of a signal on a line. Here, the switch has a single signal input and a single signal output, which is called single-pole-single-throw (SPST) configuration, as shown in figure 1(a). Many switching network circuits, however, require a switch unit to select a specific signal line out of a number of input channels (multiplexer) or to switch a signal between different output channels (demultiplexer). Typical applications are the switching of capacitor banks in filters or impedance matching networks, the switching of resistors in variable gain amplifiers, the selection of transmit and receive channels in T/R modules, or switching of delay lines in phase-shifting circuits for phased array antennas [7, 8]. A multi/demultiplexing unit capable of selecting between two channels requires a single-pole-double-throw (SPDT) switch, or, more generally, an SPnT switch unit for selecting one out of n channels. The nature of most MEMS switch designs is the SPST configuration, and a SPDT unit is usually constructed by using two SPST switches as shown in figure 1(b) with one
switch in each branch of a T-junction [9–11]. RF circuits can be optimized for a narrow frequency band by placing the (capacitive shunt) switches in each branch at a distance of \( \frac{1}{2} \) from the junction, converting the line with the switch short-circuited to ground to an invisible, thus negligible high load, which is typically used for RF SPDT switch unit [7]. More advanced SPDT circuit designs comprise even four switches, two shunt and two series switches, which results in a very broadband SPDT device [8]. Also, SP4T multi-port switch composed of four metal-contact SPST switches has been utilized to build a very low loss 4 bit phase-shifter network [12].

A ‘true’ single-pole-double-throw switch, as presented in this paper, consists of a single switch mechanism allowing for switching the input signal line to either one of the two output signal lines, as illustrated in figure 1(c).

1.2. Mechanically multi-stable switches

In principle, every SPST switch is bi-stable, since it has two well-defined stable states (on and off). However, switch designs based on active closing and passive opening mechanisms, often referred to as ‘biased switches’, have only one mechanically stable state which is the off-state for a so-called normally-off or (on)-off switch (the ‘on’ in parenthesis in the notation symbolizes that it is not a rest position). The other stable state can only be maintained by applying external energy, typically a voltage source [15]. This is the most common switch concept both in the micro-world and in the macro-world, including electromagnetic relays. Mechanically bi-stable switches make use of a switch mechanism keeping both of its states even when the energy source is removed. External energy is only needed to trigger the transition between the two stable states. Besides true zero-power consumption in the stable states, the main advantage of such designs consists of the fact that the switch state is conserved in the case of an intentional or unwanted power outage.

Mechanically bi-stable or multi-stable switches are typically achieved by multiple local minima of the mechanical energy stored in the structure (laterally buckling cantilevers, electrothermally [14–16] or electrostatically [17] actuated), by discrete re-configuration of the geometrical structure (locking mechanisms with lateral [11, 13, 18, 19] or with vertical [20] movement), or by re-configuration of discrete material properties (polarization change in a vertically moving, magnetostatic actuator [21, 22]).

Since no actuation voltage has to be provided in the stable states which allows for completely switching off their driving circuitry, mechanically multi-stable switches are very suitable for applications such as satellite-based communication modules demanding ultra-low power consumption [11]. Also, the switch configuration is not lost during power outage without requiring a battery backup system, which is an important criterion for certain applications, for instance reconfigurable telecommunication networks.

1.3. Curved-electrode actuators

Electrostatic curved-electrode actuators are based on a flexible and a fixed electrode, with the electrode distance gradually increasing from the clamped end to the free end of the moving structure. Due to the narrow gap in the beginning, high forces initialize the movement of successive parts of the flexible electrode, and the short electrode distance and thus the location of the large actuation force is moving along the fixed electrode in a zipper-like way [23–26]. Such actuators achieve very large deflection already at medium actuation voltages of 20–60 V. In contrast to electrothermal or piezoelectric actuators, both the actuation force and the restoring spring force increase with the deflection of the cantilever and reach their maxima in the end position of the movement. Thus, curved-electrode actuators are very suitable for microswitches which utilize an actuator most efficiently if the maximum contact force and the maximum opening force are provided in one and the same, i.e. the closed state of the switch [13]. The voltage of such a curved-electrode actuator can even further be lowered by a so-called starting-zone electrostatic zipper actuator, which was also utilized for a compliant buckling-cantilever bi-stable mechanism [27].

2. Device design and special features

The switch mechanism is based on three single-side clamped cantilevers. The cantilevers are arranged in-plane and the two side cantilevers are rotated by 90° to the middle cantilever. The side cantilevers comprise only one curved-electrode actuator which can deflect them toward the middle cantilever, whereas the middle cantilever is endowed with two curved electrodes and can be deflected toward either one or the other side cantilevers. With hooks at the free ends of the cantilevers, the middle cantilever can be interlocked to either the left or the right cantilever, or to none of them. This results in the three mechanically stable states, as illustrated in figure 2. With the input signal connected to the anchor of the middle cantilever and one of the two output signal lines each connected to one of the anchors of the two side cantilevers, this mechanism results in a single-pole-double-throw (SPDT) configuration with the following three stable states (on-off-on): (1) input to output 1, (2) switch off (‘tri-state’) and (3) input to output 2. Figure 3 shows an SEM picture of a fabricated device.

Because of the mechanical stability of the three stable states, the electrostatic actuators are only utilized to trigger the transition between the stable states which are maintained when the external voltage source is removed. The switches are realized in a so-called in-line or three-terminal configuration, i.e. some electrically conducting parts of the switch mechanism—here the moving cantilevers—are common electrical potential to both the signal path and the actuation electrodes. Thus, the actuation voltage and the signal to be switched must be separated either in the frequency domain which is the most commonly used method for in-line switches, or, by making
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Figure 2. The three mechanically stable states of the switch: equivalent circuit diagrams with corresponding configuration of the three interlockable cantilevers.

Figure 3. SEM-picture of a tri-stable single-pole-double-throw (SPDT, 1 input, 2 outputs) configuration with 3 curved-electrode actuators.

advantage of the mechanically tri-stable nature of the structure, in the time domain. The switches are fabricated in an all-metal process which eliminates the need for isolation layers, but requires distance-keeping stoppers along the fixed curved electrode to prevent the cantilevers from causing short-circuit or permanent electrode stiction when pulling in.

For locking and unlocking the hooks, the cantilevers have to be actuated individually in a special sequence. The actuation phases of the transitions between the on-state and the off-state are shown in figure 4 for locking/unlocking the input (middle) cantilever to the left output cantilever. The same procedure applies for latching the input cantilever to the right output cantilever. Note that both actuation voltages are removed in the stable states figures 4(e) and (a). A SEM picture with a close-up view of the center section of the SPDT switch in its off-state is shown in figure 5. Figure 6 shows the switch in one of the two on-states. Here, the input cantilever is interlocked with the left output cantilever, allowing for a signal to propagate between the input and output 1.

Curved-electrode actuators have already been utilized for lateral microswitches in earlier work [28]. There, however, the strong electrostatic force in the end position of the actuator is closing the switch contacts, and the switch is opened passively by the spring energy stored in the deflected cantilever. In contrast to such designs, the electrostatic force in the presented switch concept is not used to create the contact force, but to open the switch, as illustrated in figure 4(f), which results in a very large active opening force. The contact force is a passive force created by the deflected, interlocked cantilevers...

Figure 4. Actuation phases for switching the locking mechanism between the off-state to the on-state; for simplicity, shown for a single-pole-single-throw configuration (1 input, 1 output): (a) both the input and the output cantilever are released, off-state. To close the switch, the actuation voltage has to be applied first to the output cantilever (b), then also to the input cantilever (c), then removed from the output cantilever (d) and finally also from the input cantilever, resulting in the interlocked on-state of the switch (e). To open the switch, the actuation voltage has to be applied to both cantilevers (f), and subsequently removed first from the input cantilever (g), and finally also from the output cantilever, resulting in the initial off-state (a).

Figure 5. Close-up SEM-picture of the interlocking elements in the off-state; the cantilevers have very low spring constants of less than 10 Nm\(^{-1}\), resulting in image jitter of the input cantilever due to actuation by the electron beam in the SEM.
as shown in figure 4(c), and is therefore relatively small. Thus, unlike typical latching mechanisms in optical switches e.g., the interlocking hooks are not only utilized for mechanical bistability, but at the same time for creating the passive contact force between the switching contacts. This special concept of utilizing the actuators active and passive forces in the opposite way as in conventional switch designs makes it very suitable for soft contact materials such as gold, being known for developing large adhesion forces between the touching switch contacts [29, 30], but requiring only a small contact force for a low and stable contact resistance [31–33]. The forces of a bi-stable variant of the presented switch concept and its suitability for soft contact materials have been thoroughly investigated by the authors in an earlier study [13].

All three cantilevers are designed to be actuated at about the same voltage level. However, the input (middle) cantilever is with 400 µm longer than the two output cantilevers with 300 µm length each. The considerations behind this design decision are as follows:

- The input cantilever has a smaller spring constant resulting in a larger deflection. Thus, the main part of the contact separation (isolation) is provided by the input cantilever. The spring force of this cantilever is only utilized to restore the cantilever to its neutral position when the hooks are being unlocked.
- The output cantilevers have a larger spring constant resulting in smaller deflection (at the same actuation voltage) but also in a larger spring restoring force. As shown in figures 5 and 6, the hooks of the output cantilevers are designed to create the main part of the contact force in the interlocked position. Thus, the larger restoring spring force of the output cantilevers results in a larger contact force.

To summarize, the input cantilever provides the contact separation by having a larger deflection, whereas the output cantilevers furnish both the contact force (closing of the switch) and the release force (opening of the switch). Since the side cantilevers determine the main parts of both the opening and the contact force, the stiffness of the side cantilevers is designed for a compromise: stiff structure results in a large contact force, but stiff structure means also higher actuation voltage for opening the switch contacts. The presented design is chosen in a way that the contact force is sufficiently large for closing soft gold contacts [13, 31]. Table 1 summarizes the design parameters including forces and spring constants of the main switch design.

The shape of the curved electrodes and the stopper positions have been optimized by using a numerical simulation algorithm developed for single-side clamped electrostatic actuators, which was published and evaluated as a design tool by the authors [34]. For the presented design, the optimization criteria were to achieve sufficient deflection for generating the passive contact force, and having large active opening forces at medium-high voltage levels to overcome the contact adhesion forces for good contact reliability. The same simulation tool was also used for determining the pull-in voltages of the curved-electrode actuators. The electrode shape follows the function

$$y_{el}(x) = \begin{cases} y_0 & |0 \leq x < rL \\ y_0 + (y_1 - y_0) \sum_{i=1}^{2} a_i \left( \frac{x - rL}{(1 - r)L} \right)^{n_i} & |rL \leq x \leq L \end{cases}$$

(1)

with the parameters for the side and the input cantilever as listed in table 1.

Figure 7 shows the electrical connection schemes and the actuation signals of a mechanically bi-stable single-pole-single-throw (SPST) switch and a mechanically tri-stable single-pole-double-throw (SPDT) switch (figures 7(c) and (d), respectively), as compared to a conventional, mechanically mono-stable MEMS switch with the actuation electrodes electrically isolated from the signal path (figure 7(a)), and to a MEMS switch using a common potential for the signal path and one of the actuation electrodes in the so-called in-line or three-terminal configuration (figure 7(b)). The electrical connection schemes of the
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Table 1. Design parameters determining the electrode geometry according to equation (1), and simulated pull-in voltage, maximum deflection, stiffness restoring force for the output cantilevers (300 µm long) and the input (middle) cantilever (400 µm long), for design variant III with a total cantilever thickness of 4.6 µm, composed of 3.8 µm silicon and 2 × 0.4 µm gold coating, with a Young’s modulus of 169 GPa and 77 GPa, respectively.

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Simulation results

- Pull-in voltage V: 69.0 V, 49.5 V
- Max. deflection µm: 6.0 µm, 8.5 µm
- Spring constant µm: 7.0 µm, 3.0 µm
- Restoring force µN: 43.1 µN, 23.0 µN

Figure 8. Process flow: (a) starting from a silicon wafer, (b) DRIE etching of the trenches, (c) anodic bonding of the wafer upside-down to a glass wafer, (d) CMP of the major part of the silicon wafer, (e) etching of the remaining silicon substrate in KOH, (f) release-etching of the moving structures in HF, (g) gold coating in a sputter tool.

Figure 9 shows a cross-sectional cut through the device layer of the silicon-on-glass wafer at the position of the 5

Figure 9. Cross-sectional cut through the device layer of the silicon-on-glass wafer, showing a deep-reactive-ion-etched (DRIE) trench at the smallest electrode distance of 2 µm, resulting in a height-to-width aspect ratio of 30:1.

The switches in figures 7(a) and (b) basically also correspond to the configuration of a macroscopic electromagnetic relay (EMR) and a metal-oxide-semiconductor field-effect transistor (MOSFET), respectively.

3. Fabrication

The switches are defined by a single photolithographic step and etched into a silicon substrate which is then transferred to a glass wafer, resulting in a silicon-on-glass structure. The fabrication procedure, carried out on 150 mm large substrates, is sketched in figure 8.

The structures are etched 60 µm deep into a 750 µm thick p-type high-resistivity (>4000 Ω cm) silicon substrate using deep-reactive-ion-etching (DRIE) technique and a thermally grown silicon dioxide etch-mask (figure 8(b)). The lithography for this etch step is carried out with a 4:1 wafer stepper lithography system. Then, the wafer is covered by 200 nm wet thermally grown silicon dioxide to protect the sidewalls during a later KOH etch step (figure 8(c)). The silicon wafer is bonded to a 500 µm thick pyrex #7740 glass wafer by anodic bonding, with the etched structures facing the front-side of the glass wafer (figure 8(d)). Subsequently, the silicon substrate is thinned down by using combined grinding/polishing (figure 8(e)) and by a final potassium hydroxide (KOH) etch-step until the structures are fully exposed (figure 8(f)). The remaining silicon layer on the glass substrate is about 60 µm thick. Afterwards, the structures are released by etching the front-side of the silicon-on-glass wafer in hydrofluoric acid aqueous (HF) solution (figure 8(g)). Finally, the structures are coated with a sputtered chromium adhesion layer and a soft gold layer (figure 8(h)) with a total thickness of 450 nm, measured on the sidewalls of a 17 µm wide etched trench. For gaps narrower than 5 µm between opposing silicon walls, the metal coating thickness in the upper part of the sidewalls is still about 400 nm thick. The metal coating on the top of the silicon device layer is about 700 nm thick. Due to the undercut of the isotropically etched glass wafer, the metal coating does not form a closed layer at the bottom of the trenches, and geometrically isolated structures in the silicon device layer are also isolated electrically, which can be seen in figure 8(h).

Figure 9 shows a cross-sectional cut through the device layer of the silicon-on-glass wafer at the position of the
smallest electrode distance used in the design, which is 2 µm. The height-to-width aspect ratio of the etched trench is 30:1. In this figure, and also in figures 5 and 6, it can be seen that the KOH solution is attacking the top surface of the back-etched silicon wafer differently at the edges of the trenches. It is caused by an interaction with the crystal orientation of the 1-0-0 silicon wafer due to over-etching in KOH which is necessary to reach all of the bottoms of the etched trenches whose depths depend on the trench width determining the exposed area in the DRIE tool. This effect has no influence on the mechanical or electrical performance of the switches, but could be prevented by aligning the structures in a 45° angle to the major cut of the wafer [35].

With the presented process scheme for creating structures in a silicon-on-glass wafer, the top part of the deep-reactive-ion-etched structures ends up at the bottom of the silicon device layer after transferring it to the glass wafer. This implies that the features seen at the front-side of the switches are actually the shapes etched 60 µm down in the trenches, which explains why the hooks shown in figures 5 and 6 are not very sharp. However, it does not affect the interlocking function.

4. Device evaluation

4.1. Actuation voltage and opening forces

For the different design variants, three voltages have been evaluated: the pull-in voltage of the output cantilevers (actuation voltage according to figure 4(b)), the pull-in voltage of the input cantilevers (according to figure 4(c)) and the voltage to unlock the latched cantilever (according to figure 4(f)).

The measured and simulated actuation voltages are plotted in figure 10 for the three main design variants. For the design with the least cantilever thickness (measured total thickness of 3.6 µm, composed of 2.8 µm silicon and a gold coating of 2 × 400 nm), the measured pull-in voltages of the input and output cantilevers are 30.8 and 45.2 V, respectively. These voltages are very well reproducible with standard deviations (1 σ) of 0.59 and 0.28 V of ten successive measurements. The corresponding simulated pull-in voltages are 33.1 and 46.3 V for the input and the output cantilevers, respectively, and deviate from the measured values only by −7.4% and −2.4%, respectively. The actuation voltage required to open this switch variant is less stable and varies between 48 and 65 V for ten successive measurements, which is explained by the unstable adhesion force between the metal contacts, which varies for every switch cycle. Because of the short distance between the deflected, latched cantilevers and their curved electrodes, the actuators develop very large opening forces. The total opening force of the discussed switch variant with a cantilever thickness of 3.6 µm was determined by simulations to be 1100 µN at an actuation voltage of 57.3 V, corresponding to the average measured opening voltage. A rough estimation by assuming that the square of the pull-in voltages is proportional to the counteracting force, reveals that the adhesion force between the soft gold contacts varies between 124.6 and 568 µN.

The self-actuation voltages (switch closing from the off-state when applying a voltage between the input and one of the output contact pads, without applying any actuation voltage) were determined by measurements to be 82.8, 57.3 and 32.68 V, for the three design variants with total cantilever thicknesses of 4.6, 4.1 and 3.6 µm, respectively. The cause of the self-actuation is not the force developed between the small tips of the two cantilevers, but rather the electrostatic force between the cantilevers and their curved electrodes, which are electrically connected since they are made out of the same block in the silicon device layer and are electrically floating between the input and the output cantilever potentials. If operated only in the two interlocked states input-to-output1 and input-to-output 2 (on–on), self-actuation is completely prohibited.

4.2. Switch impedance and suitability for RF signals

The total switch impedance of the first ten switching cycles with a cold-switched signal current of 1 mA is plotted in figure 11. The impedance settles to stable 2.32 Ω after about five burn-in cycles. It is assumed that this behavior is caused by the contact surfaces which have to adapt to each other. The rather large total impedance of the switch is mainly caused by the long cantilevers consisting of high-resistivity silicon coated with a relatively thin gold layer only. For the switch variant with the softest cantilevers of a thickness of 2.8 µm Si plus 2 × 400 nm Au, the passive contact force was estimated to 15–20 µN by simulating the deflected cantilevers. This force is rather at the lower end for having a stable electrical
contact for gold [31]. However, the experimental evaluation of the fabricated switches has proven that even this low contact force is large enough for having a stable contact resistance when using soft gold contacts, since the measured impedance is stable and reproducible within less than 20 mΩ after the initial burn-in. For the design variants with a total cantilever thickness of 4.1 and 4.6 μm, the contact force is slightly larger and was estimated by simulations to 25–40 μN.

The switch design as shown in figure 3 is not especially suitable for switching RF signals, since:

- The overall switch resistance, caused by the switch contact and the two long cantilevers with a total length of 700 μm, is with 2.32 Ω relatively large for a MEMS switch. This ohmic impedance alone causes about −0.2 dB insertion loss (assuming a 50 Ω system).
- In the current design, the curved electrodes are also acting as dc and RF ground of a coplanar waveguide configuration. Since the distance between the grounds and the signal conductor (cantilever), especially in any of the two on-states, is only between 2 and 8 μm large, and since the device layer is about 60 μm thick, the capacitance per unit length is very large which results in a non-symmetric waveguide with a very low characteristic impedance of 11.6 Ω. Because this impedance discontinuity is relatively long (two cantilevers, 700 μm in total), it causes very large reflections even in low-GHz frequencies. At 4 GHz, the simulated reflections already exceed −5 dB (assuming a 50 Ω system impedance).

However, this judgment of the presented design does not conclude that the concept of the switch with cantilevers latched and unlocked by curved-electrode actuators is not suitable for RF signals. A modified concept with the curved electrodes not being a part of the RF ground conductors is possible and currently in the design phase.

4.3. Switching time

The total switching time consists of the sum of the different actuation phases as shown in figure 4 plus optional waiting steps between these phases. For evaluating the prototype devices the actuation sequence was carried out manually. However, the following paragraph gives an estimate of the overall switching times achievable with the novel switch concept.

The transition from the off to the on state consists of two active pull-in phases (figures 4(b), (c)) and two passive release phases (figures 4(d), (e)), and the transition from the on to the off-state consists of one active pull-in (figure 4(f)) and two passive release phases (figures 4(g), (a)). The resonance frequencies of the non-interlocked cantilevers were determined by simulations to be between 16.2 and 36.8 kHz for the different cantilever designs of 300 or 400 μm length and thickness of 3.6 to 4.1 μm. These frequencies are in a range comparable to the resonance frequencies of 10–200 kHz of most electrostatic MEMS switches [3, section 3.1]. Thus, the active pull-in time of the cantilevers can be estimated to 10–50 μs corresponding to typical electrostatic MEMS switches. In contrast to the pull-in time, the passive release time depends much more on the Q-factor of the resonating cantilever in atmospheric pressure [3, section 3.5]. The Q-factor is mainly determined by the gas damping which is definitively larger for the laterally moving structure as compared to typical vertically moving MEMS switch designs, because it has no etch holes reducing the damping and the gap for the air to escape at the bottom side—just defined by the under-etching of the glass wafer, process step (f) in figure 8—is very small. When considering the large gas damping of the cantilevers and their small restoring spring forces of 15–42 μN, and comparing it to the simulation results presented in [3, section 3.5], the release time of the cantilevers can be estimated to less than 150 μs. Simply adding the estimated worst-case times for the active (50 μs) and the passive (150 μs) actuation phases would result in 400 μs for closing the switch and in 350 μs for opening the switch. Even with appropriate waiting steps between the phases, the total switching time with an automated actuation sequence should be well below 1 ms. The presented switch mechanism is definitively much slower than typical electrostatically actuated switches, but still much faster than electrothermally actuated microswitches.

5. Conclusions

This paper reports on a novel mechanically tri-stable, all-metal microswitch based on laterally moving curved electrode actuators. The switches are designed in an in-line, true single-pole-double-throw configuration and features active opening capability. Test devices have been fabricated in a silicon-on-glass process and have been successfully evaluated. Due to the curved-electrode actuators utilized in their maximum-force end position for breaking the switch contacts, the switches develop a remarkably large active opening force suitable for overcoming large contact adhesion forces.

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Queries

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