Switching speed analysis of low complexity RF-MEMS switches

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Abstract — Tunable microstrip filters, phase shifting elements, and switches in the GHz range were previously realized in a low complexity technology. This paper now presents time dependent measurements of the RF-signal to evaluate the switching behavior of this technology. The measured switching time for a 300µm long cantilever in air is below 75µs. It depends on the amplitude and the sign of the DC actuation due to semiconductor effects in the actuation path that lead to a delay of 60µs before the cantilever starts to move down. This delay can be decreased by a higher voltage peak, illumination of the switches to generate additional charges, and an additional doped area. With this doped region of minority charges, the switching time can be reduced below 30µs for actuation with negative and positive sign.

The opening time is between 40µs and 20µs depending on the bending radius of the switches. The movement starts immediately after turning off the actuation voltage and is limited by the mechanic resonance frequency of the switch and the damping by the atmosphere.

Index Terms — RF-MEMS, switching speed, tunable filter, phase shifter, microwave switch.

I. INTRODUCTION

For the communication between airplanes and satellites as well as for electrically steerable antennas for radar systems, highly integrated RF-front-ends with good RF performance are needed. Electrically steerable antennas in a radar application can move the antenna beam faster than mechanical systems and thus reach higher frame rates. Further on, a phased array antenna is flat or can even be conformal which is important for putting the antenna on top of an airplane.

RF-MEMS elements are good candidates for certain building blocks of these antennas. They have shown very good RF-performance in microwave applications in terms of low insertion loss and high linearity [1]-[2]. They have very low power consumption and thus allow a high element density without thermal problems. But there are still some challenges for RF-MEMS like their limitations in switching speed, their high actuation voltage for electrostatic actuation, or their complex packaging. Also their reliability has to be proven and many concepts have problems with higher RF-power handling.

Using a very simple processing technology might be an approach to overcome many of these challenges. As previously demonstrated in [3]-[4], a low complexity technology was used to realize microwave filters, phase shifting and switching devices. In this paper, the switching time and behavior of these devices is evaluated.

II. PRINCIPLE OF OPERATION

The RF MEMS devices consist of a clamped-free aluminium silicon sandwich with an intrinsic stress gradient such that the free parts bend up (Fig. 1). The device is built on high resistivity silicon with silicon oxide as dielectric on top. Below the tip of the movable cantilever there is a second thin metallisation layer as path for the RF-signal.

![Fig. 1 REM- picture of a bended series switch](image)

There are no additional bias electrodes necessary, because the actuation voltage is applied between the top metallisation and the backside. The high resistivity silicon acts as a dielectric in the RF regime, but can transport the charges for the DC actuation. The electric field that pulls the bended beams down to the substrate is effective entirely between the oxide and the air gap. At the anchor of the bending structure the pull-down force is highest because the air gap is smallest. During switching, the cantilever starts to roll down from this point, which leads to suitable actuation voltages of e.g. 30V. A second advantage of the rolling movement is that the air below the switch is pushed out to the tip of the cantilever and thus it is not a typical squeeze film damping situation that limits in other cases the switching speed.

Depending on the length of the bending cantilever a large actuation path can be reached. A typical tip height of a 300µm long beam is 17µm.

At last, a rather high restoring force is available, which results in a high release voltages of about 70% of the actuation voltage.
III. REALIZED DEVICES AND CIRCUITS

This technology offers the possibility to lift parts of microstrip or coplanar transmission lines into the air above the substrate. By applying the actuation voltage, the bended parts can be switched down to the substrate. This element can be used to realize a capacitive series switch with a big series capacitance in the down-state and a small parasitic capacitance in the up-state [4]. A similar device is also used for the switching speed measurements. Another effect is that a line that is lifted up in the air changes its electrical length, because the effective $\varepsilon_r$ becomes smaller. This effect can be used to build switchable filters [6]. With the relatively large actuation path a large frequency shift of about 20% of the operation frequency can be reached. The left picture in Fig. 2 shows a switchable band-stop filter in microstrip configuration, where the ends of the resonant line can be switched and thus the resonance frequency is shifted. Another application is phase shifters [3]. On the right side of Fig. 2 there is a coplanar line phase shifter that changes the phase for 22° at 35GHz with a maximum insertion loss of –0.33dB.

IV. SWITCHING SPEED

The switching behavior of RF-MEMS is of interest for many applications, e.g. when used as phase shifters in electrically steerable antennas whose scanning speed is limited by the switching time. Air damping and the mechanical resonance frequency of the movable parts are the main limiting factors [5]. Operated in low pressure environment the switching speed can be increased, but bouncing becomes a negative effect.

a. Measurement Setup

The time response of 300µm long and 70µm wide switches with no holes was measured with a 35GHz signal that was monitored using a Schottky diode converter and an oscilloscope. The actuation is an amplified alternating positive and negative square signal from a function generator with 1ms negative voltage square, 1ms off, 1ms positive voltage square and again 1ms off (Fig. 3, small picture). An LC-block protected the signal source from the actuation voltage. Due to the LC-block, the actuation voltage applies at the switch 13µs after the signal is set at the frequency generator.

b. Opening of the Switch

The opening speed was measured for two different series switch designs with different intrinsic stress gradients, resulting in actuation voltages of 37V (switch A) and 70V (switch B), respectively.

As high resistivity silicon is used as substrate material and no additional actuation electrodes are implemented to apply the ground signal for the actuation but the backside of the wafer, the resistance of the substrate is in series with the oxide capacitance.

The RC time constant for the $4k\Omega$cm substrate is calculated to be 2.1µs for the capacitance of the switch in the down state across the silicon oxide.

![Fig. 3 Opening behavior of switch A after different applied actuation voltage amplitudes. Small picture: whole actuation pattern in 4ms.](image)

The opening time depends mainly on the mechanical resonance frequency of the beam and the damping of the atmosphere. It is independent of the amplitude and the sign of the switching voltage that was applied before to actuate the cantilever. The movement of the switch starts immediately with turning off the actuation voltage and takes about 40µs for switch A (Fig. 3) and less than 20µs for switch B (Fig.4).

![Fig. 4 Opening of switch B with smaller bending radius and more restoring force is faster but shows bouncing for 100µs.](image)

Switch B is faster in the opening movement. This can be explained with the higher restoring force, corresponding with the higher release voltage, and with a reduced air damping. The air damping occurs mainly
close to the area where the cantilever is being lifted off the substrate during the opening movement in a squeeze film like manner. The air has to fill the gap between substrate and cantilever. For switch B with the smaller bending radius this area is smaller thus, the damping is reduced. Switch B shows furthermore a weak bouncing effect in the up-state that lasts for 100µs which is another indication of reduced air damping. A bouncing frequency of 43kHz was observed.

The optimum mechanical switching behavior is achieved when the spring constant of the cantilever and the damping of the air result in a critical damping [7].

Besides the amount of bending, also the geometrical design has an influence on the bouncing behavior. The series switch of Fig. 1 that consists of three thin cantilevers with a connecting beam on the tip has a higher mechanical Q-factor and thus shows bouncing effects in the up-state even with the weak bended cantilevers. In the down-state bouncing could not be observed. To get more accuracy in terms of the damping effects, tests in reduced pressure environment can be made in the future.

The influence of the geometry of the cantilevers on the switching time has been extracted by measuring the closing time of cantilevers with widths varying from 60µm to 200µm. The time for a switch to move down to the substrate increases in the measured range of widths linearly by 5µs (narrow to wide cantilever). For a switch design that is optimized for switching speed this can be taken into account with openings in wide structures.

c. Closing of the Switch

The time response of the closing is more complex and depends on the sign of the applied actuation voltage. Therefore, negative and positive switching pulses will be described separately. The backside contact is always on ground potential, the actuation voltage is applied on the RF-line.

- Negative actuation pulse: To build up the potential for negative switching pulses an inversion channel has to be created. The time for this is limited by the generation rate of holes in the high resistivity n-type silicon. This is confirmed by the observation that illuminating the wafer with light can decrease the switching time. A photon that is absorbed in the silicon can create an electron-hole pair, thus speeds up the generation rate of holes in the high resistivity n-type silicon. For fast switching times and at the same time avoiding extra charging of the dielectric layer, high bias voltage was applied for a few 10µs to reduce the delay time and was then reduced to the necessary switching voltage.

Fig. 5 Closing of the switch with negative actuation: Influence of higher actuation voltage, from –37V to –43V, the delay time decreases and the movement gets faster

To suppress this semiconductor effect, a highly doped region with minority charges was implemented in the anchor region of the switches (Fig. 6, small picture). This region is a reservoir of minority charges and also increases the area where minority charges are collected. They can be transported laterally below the oxide from the anchor region of the switch.

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Fig. 6 presents the measured switching behavior for switches of type B with and without additional doped area below the anchor of the switch (small picture) and high enough voltage to avoid the delay time. No difference in switching time is observed if illuminated. If not illuminated, switches with doped area are 10µs faster than without.

Fig. 6 Switches of type B with and without additional doped area below the anchor of the switch (small picture) and high enough voltage to avoid the delay time. No difference in switching time is observed if illuminated. If not illuminated, switches with doped area are 10µs faster than without.

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Fig. 6 presents the measured switching behavior for switches of type B with and without doped area with and without illumination with light. For an actuation voltage of 80V, the delay time disappears completely. If the generation rate for holes is high enough due to an illumination of the wafer, no difference can be seen weather the anchor region is doped or not. The switches are closed 20µs after the voltage is applied. For not illuminated switches, the doped ones show a 10µs shorter closing time than switches without doped area.
Also, it was found that switches with doped area show a more reproducible switching time than switches without doped area. The reason for that is not clear at the moment.

![Switch in up-state and down-state](image)

**Fig. 7 Actuation with positive voltage, with and without additional doping area, titanium aluminium sandwich on the backside, identical switch as in Fig. 6**

- Positive actuation pulse: Switching with positive actuation voltage should be faster because no minority charges have to be generated in the substrate. But there was also a delay of up to 100µs observed due to the silicon aluminium Schottky contact at the backside of the wafer. This diode behaves for positive actuation in reverse direction like an additional resistor that leads to a RC time constant of several 10µs. An additional titanium layer between the silicon and the aluminium at the backside contact decreases this effect considerably. It reduces the Schottky barrier, thus the diffusion current is increased. To avoid the Schottky diode completely, a doping of phosphor on the backside can be done to get an ohmic contact.

The doped area close to the anchor of the cantilever that was introduced to decrease the switching time for negative actuation voltages also speeds up switching with positive one while the Schottky barrier is present (Fig. 7). An explanation is that without doped area, in the moment when the actuation voltage is applied, first the capacitance at the anchor region where the electric field is highest is filled with electrons before the electrons are available for the switching region. With a highly doped area of holes, the holes get pushed through the backside contact, the fixed negative charges compensate the electric field in the anchor region, and collecting electrons for the switching region can start immediately. The holes do not recombine with the electrons coming through the Schottky barrier because of their long lifetime in high resistivity silicon. So these electrons are additionally available in the switching area.

The doped region below the RF-line did not show any influence on the losses as long as the region is completely covered with the metallization. Doped regions next to RF-lines increase the line losses.

V. CONCLUSION

The switching behavior of RF-MEMS devices built in a very low complexity RF-MEMS technology and using a bended clamped-free aluminium silicon cantilever was investigated.

Air damping and the mechanical properties of the cantilevers mainly dominate the time, which is necessary to open the switch. Smaller bending radius not only results in higher restoring force but also in reduced air damping, also causing bouncing due to the increased mechanical Q-factor. The opening time in ambient atmosphere is below 40µs for 300µm long switches with 37V actuation voltage and 20µs for switches with 70V.

The observed closing time of 70µs is mainly dominated by an electrical delay time due to semiconductor effects. It was shown that this delay can be reduced by applying a high voltage peak. Another solution is to implement an additional doped area of minority charges below the anchor region of the bended cantilevers. This reduces the switching time to below 50µs without additional voltage peaks. A closing time of 20µs was demonstrated, with additional voltage, doping, and illumination with light. The actual mechanical closing time from 10% to 90% of the output signal is below 10µs.

These results compare favorably to switching times of conventional clamped-clamped beam designs.

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REFERENCES