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Development of High C_{on} C_{off} Ratio RF MEMS Shunt Switches

F. GIACOMOZZI[1], C. CALAZA[1], S. COLPO[1], V. MULLONI[1], A. COLLINI[1], B. MARGESIN[1], P. FARINELLI[2], F. CASINI[2], R. MARCELLI[3], G. MANNOCCHI[4], L. VIETZORRECK[5]

[1] FBK, Via Sommarrive 14, 38050 Trento, Italy
E-mail: giaco@itc.it

[2]University of Perugia, DIEI, Via G. Duranti 93, 06125 Perugia, Italy
E-mail: paola.farinelli@diei.unipg.it

[3] CNR-IMM Roma, Via del Fosso del Cavaliere 100, 00133 Roma, Italy
E-mail: romolo.marcelli@imm.cnr.it

[4]Thales Alenia Space Italia, via Saccomuro 24, 00131 Roma, Italy
E-mail: giovanni.mannocchi@aleniaspazio.it

[5] Technische Universität München, Lehrstuhl für Hochfrequenztechnik, Arcisstr. 21, D-80333 München, Germany
E-mail: vietzorreck@tum.de

Abstract. This paper reports on the successive improvements introduced in the **shunt** switches fabricated with the RF MEMS multiuser technology platform available at FBK. In the course of a multiyear development several technological features and design methods have been made available to enhance the operation of capacitive switches. This work analyzes their effects by reviewing the behaviour of the FBK capacitive switches at three different stages of this optimization process. Improvements have been assessed by means of DC electromechanical characterizations, which use a simple quasistatic C-V measurement to extract the switch actuation voltage and the capacitance in the on and off states (C_{on} and C_{off}) and RF measurements. The addition of a floating metal layer into the process flow has allowed a great increase of the switch on state capacitances, getting C_{on}/C_{off} ratios of 200, up to 50 times greater than the ones obtained for the same structures without this feature.

Key words: RF MEMS, Capacitive switch, Surface micromachining, Electromechanics.

1. Introduction

RF MEMS switches demonstrate better electrical performance and lower power consumption than their solid-state counterparts on equal size scales. The use of low resistivity metal beams combined with thin air gaps between switching parts provides high isolations (> 20 dB) and small insertion losses (< 0.2 dB). The non-linearity that are associated with semiconductor junctions in PIN diodes or GaAs FETs are not present except for the slight hysteresis that can be noted on CV characteristics of capacitive shunt switches. The high integration levels, non measurable harmonics or intermodulations and negligible quiescent currents further improve the overall performance of the RF MEMS switches. Nevertheless, the lower RF power handling capability, lower switching speeds, higher actuation voltages (> 10 V) and inferior reliability are issues that still prevent the widespread use of RF MEMS in many applications [1].

MEMS shunt capacitive switches typically show very low loss and excellent transmission characteristics since in the up-state they mainly consist of a continuous signal line with a low shunt capacitance (C_{off}) [2]. On the other hand when the switch is activated it capacitively short circuits the RF signal to ground, thus providing excellent isolation even at high frequencies. Nevertheless, there can be many factors limiting the switch performance. In particular, the down state capacitance (C_{on}) is often degraded due to surface roughness and local bending of the movable bridge.

This paper describes the enhancements introduced in the course of the multiyear development of the RF MEMS fabrication process offered by FBK-irst and the design solutions adopted to obtain shunt capacitive switches with very high and repeatable C_{on}/C_{off} ratio.

Firstly, it will be analysed the performance observed using the original process, which has allowed the identification of the main technological issues that limit the function of shunt switches. These results will be compared with the ones obtained with the same design using an optimized revision of the fabrication process, which includes the deposition of a floating metal electrode on top of the dielectric in order to obtain a very high and repeatable down state capacitance.

Section 4 will present the performance of a shunt switch structure that has been specifically designed to take full advantage of the benefits offered by the floating metal step, the so called boosted design. Devices have been assessed by DC electromechanical characterization, using a quasistatic CV measurement [3] to extract the actuation voltage and the capacitance in on and off state (C_{on}, C_{off}), and by RF measurement. Finally, the optimized RF MEMS fabrication process is described.

2. Original design

In the first MEMS fabrication cycle the shunt capacitive switch consists of a tapered shape air-bridge anchored to the CPW ground planes (Fig. 1). The central conductor of the CPW line under the air-bridge is made up of a metal multilayer covered with a 100 nm LTO dielectric layer, which provides the capacitive short circuit of the RF signal when the bridge is actuated in down state (C_{on}).

The switch is actuated by lateral pads isolated from the RF line. The separation of DC and RF signals reduces the self-actuation risk because the overlap between signal line and bridge can be kept small without influence in the actuation voltage. However the overlapping area needs to be properly designed since in such a configuration it determines the C_{on} capacitance and thus the operating frequency band.

Figure 1 shows the shunt switch originally designed, whose theoretical C_{on} is 4.6 pF and consequently the down state resonance frequency is around 11 GHz.

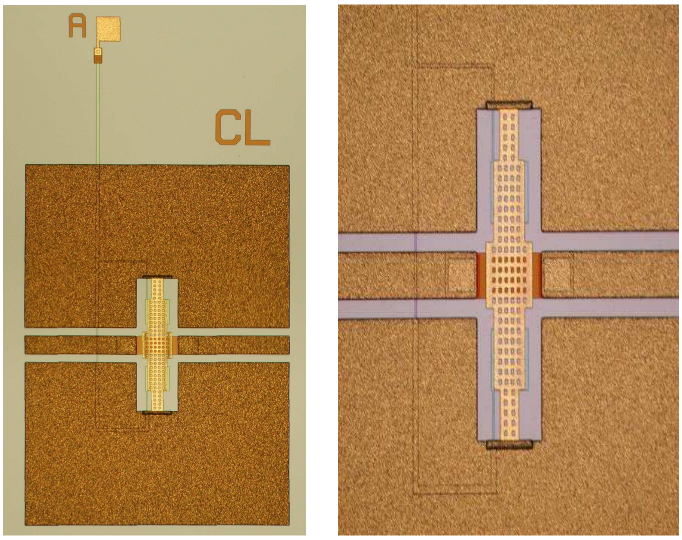
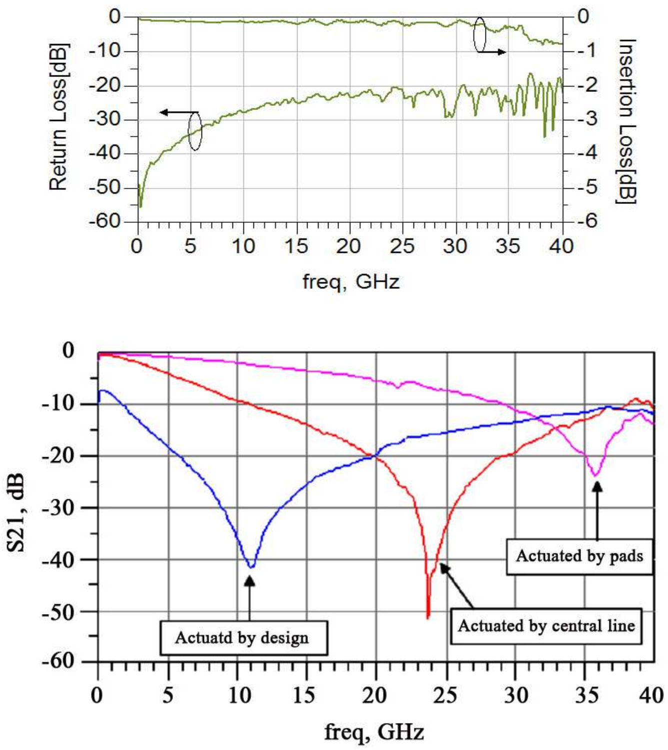


Fig. 1. Photo of a shunt capacitive MEMS switch fabricated at FBK.

As shown in Fig. 1 10×10 μm^2 square holes are uniformly distributed over the air-bridge in order to enable the complete removal of the sacrificial layer supporting the switch membrane during fabrication. Moreover the holes increase the actuation speed by reducing the air damping. The measured S-parameters of this first design of shunt switch are presented in Fig. 2a for the switch in up state. Figure 2b shows the comparison among the isolation behaviours of identical switches when actuated by design (bridge deposited without spacer layer), when actuated applying a bias voltage on the two lateral pads and when actuated on the CPW line central conductor using a bias T. The actuated by design switches behave as designed. On real devices a severe shift in the resonance frequency was observed indicating a significant degradation of the C_{on} capacitance, which depend also on the position of the applied actuation force. The measured C_{on}/C_{off} ratio was thus very low, around 3 in the case of lateral actuation and around 8 when central force was applied.



a)

b)

Fig. 2. Measured S parameters of the shunt MEMS switch: (a) transmission, (b) isolation when the bridge is actuated by design, by applying voltage on the central conductor of the CPW line or by applying voltage on the lateral electrodes respectively.

3. Modelling of the C_{on} degradation

A specific investigation has been carried out to obtain a simplified model of C_{on} capacitance as a function of physical parameters. The strong reduction of C_{on} has been attributed to a residual air gap H_{res} between the switch membrane and the underpass region which lead to a lower capacitance. Three major contributions have been identified, , namely the height disparity between the actuation electrodes and the underpass H_{step}, the surface roughness of the underpass dielectric H_{rugh} and the non-planarity of the metal bridge H_{def} (shape factor). A general expression for the residual air gap H_{res} is therefore:

$$H_{res} = H_{step} + H_{rugh} + H_{def}$$

H_{step} is the gap due to the height disparity between actuation electrodes and underpass line. The geometry of a collapsed bridge is schematically depicted in Fig. 3, where the dimensions of the two axes are not shown in the same scale. The bridge almost lays flat over the electrode area due to the electrostatic attraction force that holds the bridge down. In contrast on the underpass region there is not vertical force that holds the bridge down and its rigidity hinders the complete collapse. The unique vertical force acting on the bridge structure outside the actuation electrode is the force generated by the bending of the bridge in the region between actuation electrode and underpass. By performing a parameter fitting between the measured capacitance and the equivalent circuit it was estimated that the total residual air gap was about 0.3 μm for the switches realized with a 0.2 μm thick TiN underpass, and 0.73 μm for the switches with the new 0.7 μm thick multilayer underpass, using in both cases 0.63 μm thick polysilicon actuation electrodes.

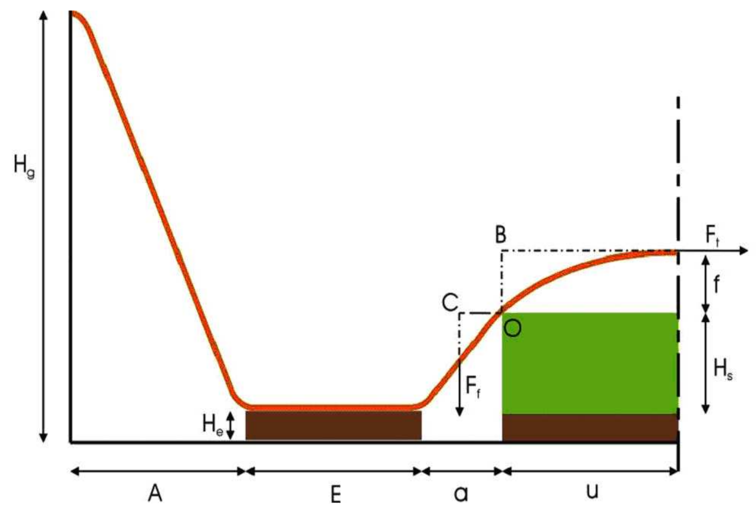


Fig. 3. Model of the left half of a bridge collapsed on top of the actuation electrode and underpass metal.

H_{rugh} is the residual gap due to the surface roughness of the underpass dielectric. The roughness prevents the bridge from contacting well the dielectric thus reducing the effective C_{on} capacitance. Material roughness can be reduced by planarization techniques, but not totally avoided. To reduce the roughness of the multilayer underpass the decrease of the aluminium deposition temperature was effective. By depositing the aluminium at room temperature it was possible to reduce roughness to 23.0±1.8 nm, which still brings to a frequency shift of 8.5 GHz.

The last contribution to the frequency shift is due to the non-planarity of the bridge. The H_{def} contribution is a result of the warp of the gold due to relaxation of the residual stress gradients and, as shown in Fig. 2, it can be reduced by applying the actuation voltage in the central conductor of the CPW line keeping the bridge flat over the underpass section. This contribution can be diminished reinforcing the bridge in the central section using the CPW gold layer, and can be totally removed by adopting a modified fabrication process with a floating metal electrode.

4. Optimized designs with floating metal

With the aim of inhibit the resonance frequency shift observed a new design was developed which includes the deposition of a 150 nm thick gold electrode on top of the 100 nm thick LTO passivation before the spacer deposition. This extra metal plate acts as an electrically floating electrode. When touched even only in a single point by the gold bridge, it takes on the RF ground potential providing the required C_{on} capacitance. Since this metal is directly deposited and not mechanically movable, it will be in close contact with the isolation layer, yielding an optimal down-state capacitance, that is not affected by the degradation due to the surface roughness or the local bending of the movable bridge. This floating electrode solution also reduces the stiction problem due to charge trapping in the dielectric layer, which is the most important failure mechanism in capacitive shunt switches. This concept was originally developed by IMEC [4] and in the frame of the FBK technology platform it has been adapted and optimized for shunt switch design.

The RF measurement with the new switch is shown in Fig. 4 in comparison with the ADS-Momentum simulation of the switch. Note that in the down state, due to the floating electrode the switch shows a high C_{on} capacitance of 1.86 pF, which is equal to the theoretical parallel plate capacitance designed. The DC electromechanical measurements have shown C_{on}/C_{off} ratios better than 95; while with the first revisions of the process it was lower than 8.

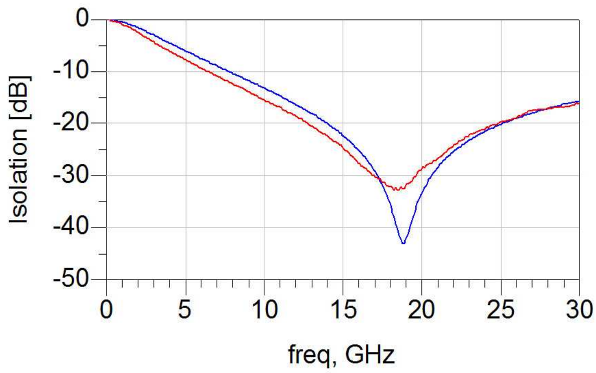


Fig. 4. Shunt capacitive switch with floating electrode: comparison between measurements and ADS-Momentum simulations in down state.

The concept of the floating metal has the additional advantage that the area overlapping the moving bridge and the signal line does not establish the value of the down-state capacitance and, therefore, in the central section it can be designed as a very narrow bridge to minimize C_{off} capacitance. This type of structure, the so called boosted design Fig. 5, further reduces the self actuation risk and improves the switch transmission characteristic. Figure 6 shows the measured RF performance of the boosted design both in up and down state. Note that in the up state, the floating electrode does not interacts with RF signal, showing an insertion loss equal to 0.2 dB at 20 GHz (including the loss due to the 1.3 mm CPW line) and a return loss better than 30 dB in the 0–30 GHz frequency band. In the down state, the bridge realizes a capacitance of about 7.7 pF, leading to a C_{on}/C_{off} ratio higher than 200.

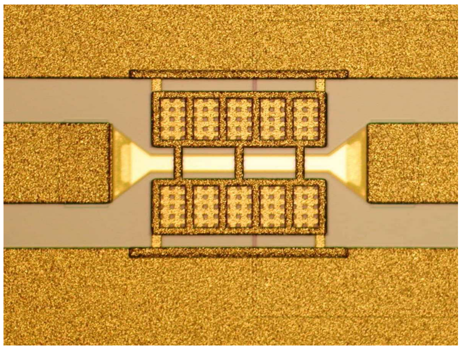
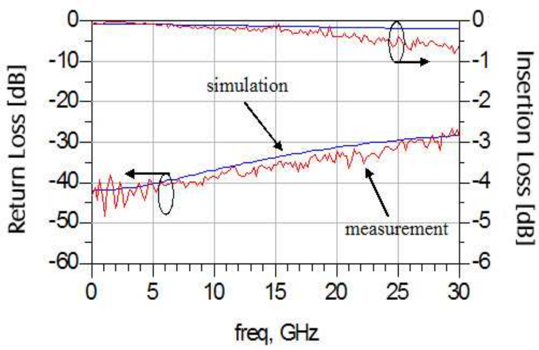
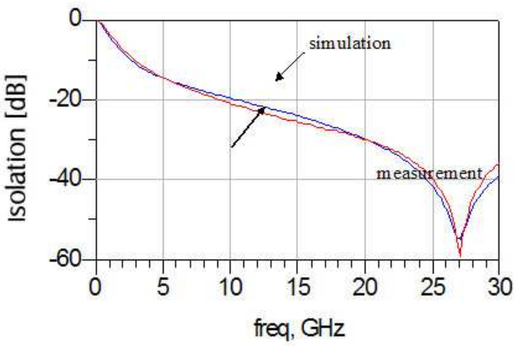


Fig. 5. Picture of a boosted switch.



a)



b)

Fig. 6. Switch with boosted design and floating electrode: measurements and ADS-Momentum simulations in up (a) and down state (b).

5. Technology

The result of the eight mask process used for the fabrication of RF MEMS switches at FBK-irst is shown in Fig. 7.

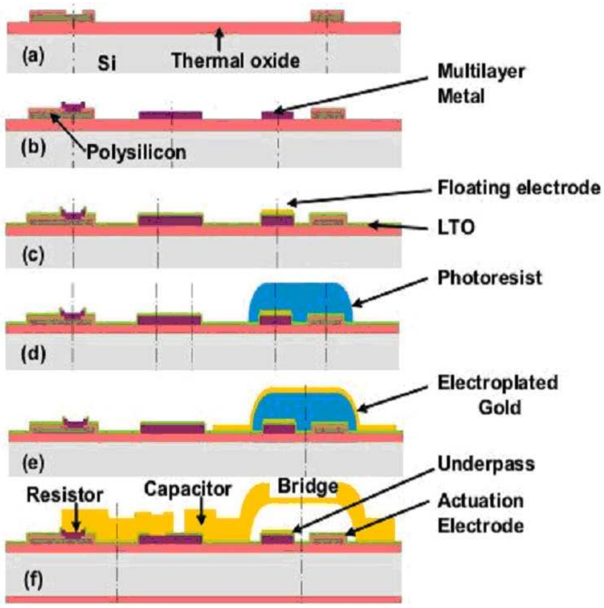


Fig. 7. Schematic diagram of the FBK RF MEMS fabrication process.

Microelectromechanical devices are fabricated on high resistivity (5 kΩ·cm) p-type silicon substrates, and can be optionally integrated with passive components. An initial thermal oxidation (1000 nm) is followed by the deposition of a high resistivity LPCVD polysilicon (630 nm) layer that is later patterned to create the actuation electrodes and biasing resistors. A 300 nm thick TEOS oxide is deposited and patterned to open the contact holes. Subsequently, the underpass metal lines, which connect the central conducting line of the coplanar waveguides (CPW) under the switches, are patterned on a complex sputtered metal multilayer composed of a Ti-TiN (30–50 nm) diffusion barrier, a low resistivity Al:Si layer (440 nm) and a capping layer of Ti-TiN (30–80 nm). Thus, this multilayer equals the thickness of the previously deposited polysilicon film. Later, a layer of 100 nm of Low Temperature LPCVD Oxide (LTO) is deposited and via holes are patterned on it. The switch reliability will strongly depend on the quality of this insulator, as imperfections can lead to charging trap effects that can produce drifts in the actuation characteristics, or even stiction events. A 3 μm thick photoresist hard backed at 200°C for 1 hour is used as sacrificial layer. The movable bridge is build on top of it. First, a seed layer (3–25 nm Cr-Au) is deposited by PVD, and the movable parts are patterned on it making use of thick photoresist. The electroplating of a first 1.8 μm thick Au layer follows. The deposition parameters are chosen to obtain the needed tensile stress. Reinforcements and anchor posts can be created taking advantage of a second electrodeposition step, which defines the CPW lines with a 3.0 μm thick gold layer. The total gold thickness can be 4.8 μm in selected portions. After removal of the seed layer the switches are released by a modified plasma ashing process to prevent stiction.

The fabrication process has recently incorporated the deposition of a thin gold layer (150 nm) used as floating electrode on the underpass regions, making feasible the attainment of predictable capacitances also in the down state. This layer can be also utilized to coat exposed metal contacts (vias) to improve the gold-multimetal interface.

6. Conclusions

Floating metal electrode is essential for capacitive shunt switches, not only to maximize their C_{on}/C_{off} ratio but also to make the down state capacitance predictable and highly repeatable. In addition such a solution allows the design of boosted switches reducing the charging and self actuation effects, which are the main failure mechanism of shunt capacitive MEMS switches. In this paper the different stages of the development of MEMS capacitive switches was presented, leading to the design and manufacturing of switches with excellent transmission characteristics and C_{on}/C_{off} ratio higher than 200.

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