Interdigitated Low-Loss Ohmic RF-MEMS Switches

R. Gaddi*, M. Bellei*, A. Gnudi**, B. Margesin*** and F. Giacomozzi***

* Centro di Ricerca "Ercole De Castro" (ARCES), University of Bologna
Via Toffano 2, 40125 Bologna, Italy, rgaddi@arces.unibo.it
** Dipartimento di Elettronica Informatica e Sistemistica (DEIS), University of Bologna
Viale Risorgimento 2, 40136 Bologna, Italy, agnudi@deis.unibo.it
*** ITC-irst, Via Sommarive 18, 38050 Povo (Trento), Italy, margesin@itc.it

ABSTRACT

An interdigitated design for MEMS RF-switches is applied to both a shunt and a series ohmic contact configuration. Interdigitated Al-Ti-TiN RF-signal paths and poly actuation electrodes are arranged underneath an electrodeposited gold plate, suspended by four thinner gold beam springs. Ohmic contact occurs at pull-in between the gold plate and the RF-signal elecrodes only. Measurements show insertion loss better than 0.8 dB and isolation better than 20 dB up to 13 GHz. Extracted lumped element equivalent circuits show intrinsic contact resistances of 1.6 Ω in the shunt and 4.5 Ω in the series switch. The interdigitated topology of RF-signal and actuation electrodes results in uniform contact pressure distribution and consistently low contact resistance.

Keywords: rf-mems, switch, ohmic, low-loss, model

1 INTRODUCTION

RF-MEMS switches have emerged in recent years as a potential alternative to solid state devices for improving reconfigurability in multistandard wireless systems [1]. Key specifications in this respect are isolation between the two RF-ports in open state and insertion loss of the closed switch [2]. Furthermore, compatibility with RF-CMOS circuitry for system-on-package integration would also require low actuation voltages, while simultaneous multistandard terminal operation would require specific transient response times. Compared to capacitive switches, ohmic contact based switches tend to be more broadband and have a better isolation vs. transient time trade-off. Besides, achieving a consistently low and repeatable contact resistance is still an issue to be addressed in terms of technology and topology design. Recently reported low loss ohmic switches were achieved through the use of a special technology including dimples on one of the electrodes during fabrication [3]. This paper presents an alternative solution for achieving low insertion loss while maintaining high isolation. An interdigitated topology for the signal and actuation electrodes is adopted with the aim of obtaining a uniform electrostatic pressure across the suspended switch element, therefore resulting in consistently low contact resistances.

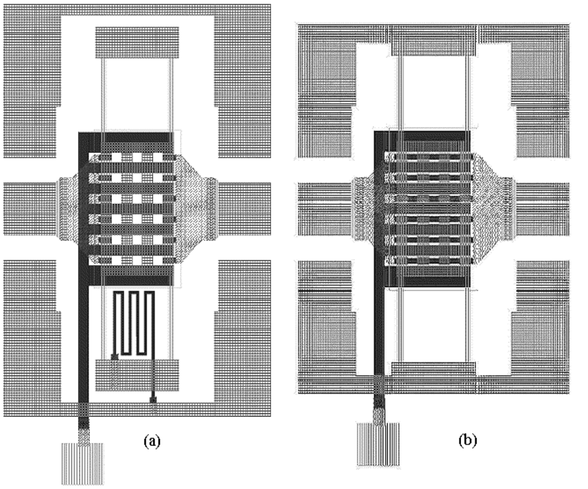

Figure 1: Layouts of the series (a) and shunt (b) interdigitated ohmic switches.

2 DEVICE DESCRIPTION AND CHARACTERISATION RESULTS

The technology process utilised for the fabrication of the ohmic switches is based on electrodeposited suspended gold membrane layer, one high resistivity poly layer for actuation electrodes and a Al-Ti-TiN multilayer for RF-signal path. Detailed process description is given in [4]. The shunt and series switch differ only for the topology of the RF-signal electrodes. The layouts of both topologies are shown in Figure 1. Input and output RF ports are physically connected by the signal fingers in the shunt switch. On the other hand, the series switch has two isolated RF ports by physically interrupting the signal fingers. The switch is therefore normally open. In both cases, direct contact is allowed only between the plate and the signal electrodes, by rising the signal metal above the level of the poly. This is achieved by placing poly dummy rectangular bricks underneath the part of the signal electrodes directly underlying the suspended plate. The actuated plate will rest on top of the signal electrodes and will not reach contact with the actuation pads.

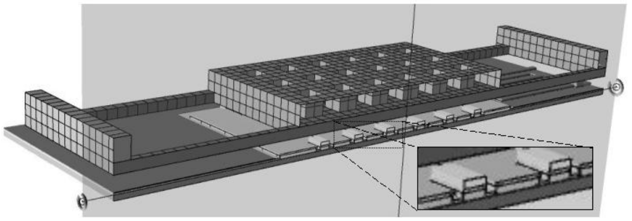

Figure 2: 3D model of the series-ohmic MEMS switch showing a section across the contact area.

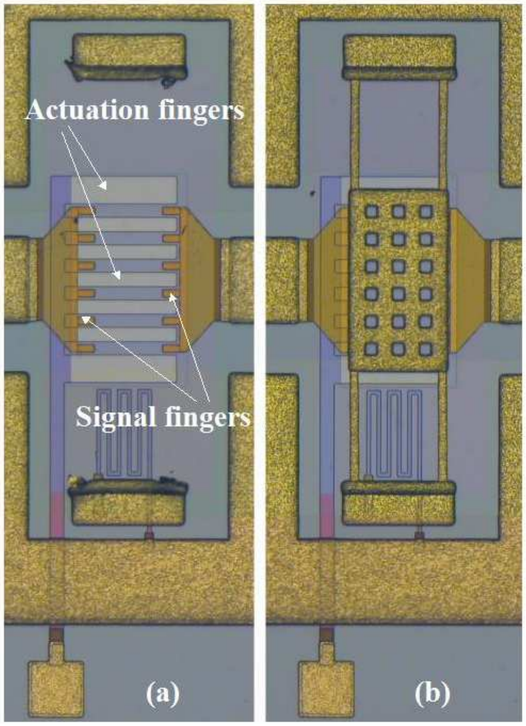

Figure 3: Series-ohmic MEMS switch with suspended plate removed (a) and present (b).

The top LTO layer is also removed from the whole area underneath the plate, through the contact via etch step, allowing direct Au-TiN ohmic contact. A cross section of the interdigitated electrodes topology is shown in the Coventor™ FEM 3D model of Figure 2. A $5\mu m$ thick electroplated gold layer is used for the plate to improve its rigidity, while thinner $(1.5\mu m)$ gold implements the four beam springs. In the shunt configuration, the plate collapses and touches the signal fingers creating a low resistance path to ground that blocks the RF signal. On the other hand, in the series switch a high-resistance bridge-to-ground path is present, through a $40k\Omega$ meander poly resistor. This avoids short-circuiting the RF signal when the plate collapses. Therefore, the actuated plate realises a low resistance path between the two RF ports, closing the switch.

Figure 3 shows pictures of a series-ohmic switch, as fabricated and after the removal of the suspended gold plate for showing the underlying interdigitated electrodes. The devices have been characterised through RF-probing using ground-signal-ground (GSG) configuration. S-parameters were measured from 0.5 to 13.5 GHz, and trough-reflect-match (TRM) calibration was carried out using trimmed gold standards on an alumina substrate. The applied actuation voltage was stepped through a double ramp in order to characterise both device's pull-in and pull-out behaviour. At each voltage step a complete frequency swept s-parameter measurement was taken.

Figure 4 shows s-parameter measurement results for the series switch, at the frequency of 2GHz, during pullin and pullout biasing. The sharp pull-in and pull-out electrical behaviour gives good hints on the correct functioning of the device, both in terms of the mechanical eletro-mechanical collapse and of the ohmic contact formation. Similar behaviour is observed for the shunt switch. Nonetheless, the latter shows generally better performances. Insertion loss better than 0.8dB up to 13.5 GHz, and better than 0.35dB between 2GHz and 4 GHz, is measured and repeatable. Isolation better that 20 dB up to 13.5GHz, and around 25dB below 4 GHz, is also measured and repeatable. On the other hand, both insertion loss and isolation of the series switch are fractionally worse. Pullin voltage is around 29V for both series and shunt switches. This value agrees with 3D FEM simulations provided a tensile residual stress in the suspended gold layer of 145 MPa is taken into account. Results from mechanical characterisation also confirm the presence of a residual tensile strain, which is believed to originate from the thermal annealing steps that follow gold electrodeposition. The design of lower actuation voltage devices with meander spring structures is currently under way, although a trade-off between actuation voltage and transient times is being considered.

Frequency domain s-parameters of the open and closed shunt switch are compared in Figure 5. From measured frequency domain s-parameters, lumped element equivalent circuits are directly extracted for both switches, in the actuated and non-actuated states. The circuit topology is assumed to be a succession of alternating Π and T shells, the outer one being associated to the shunt parasitic capacitance due to the GSG pads. The direct extraction procedure is based on subtracting Y- and Z-parameter matrixes from the measurements until all obtained lumped element values show a constant behaviour versus frequency [5]. Figure 6 shows the extracted equivalent circuits for both open and close shunt and series ohmic switches. Figure 7 compares measured and simulated s-parameters, in terms of isolation and insertion loss, for all extracted circuits. Simulations were performed using Spectre™ simulator in the Cadence™ environment. The shunt switch insertion loss is dominated by the series inductance and resistance of the parallel fingers connecting the two RF-ports. Their extracted values are 200pH and 0.85Ω re-

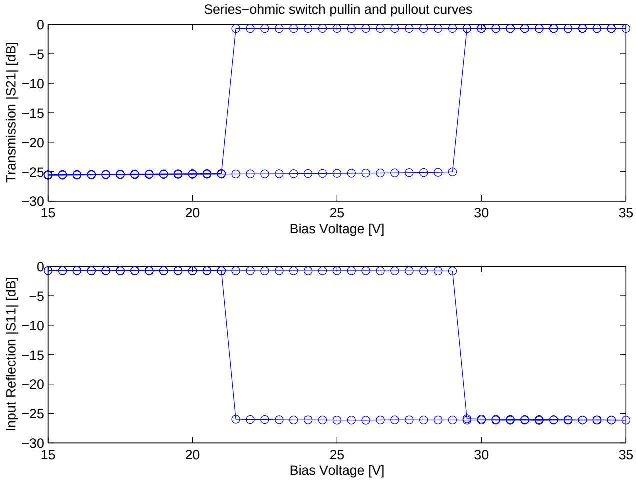

Figure 4: Measurement results at F=2GHz of reflection and transmission pullin and pullout of a series-ohmic switch.

spectively. When the switch is actuated, the intrinsic contact to the grounded plate has a 1.6Ω series resistance and 30pH inductance.

Isolation of the series switch is on the other hand given by the coupling between the two unconnected RF-ports. The extraction identifies one purely capacitive coupling of about 35fF. Improving isolation would therefore require increasing the distance between the two ports' electrodes. The down-state switch shows a series resistance between the two intrinsic RF-ports of 4.5Ω and an inductance of 280pH. This higher value is only partially due to having two contacts in series between the RF-ports, and partially to a reduced contact area compared to the shunt configuration ($\frac{1}{3}$ factor). Further studies are under way to better characterise contact resistance in terms of its dependence on pressure and contact area. From Figure 6 (c), it also emerges that the up-state series switch is not symmetric. This is due to a coupling RLC series network which is present only at the first RF-port. The overlap between the signal and actuation layers, which can be observed from the layout in Figure 1, is believed to be the origin of this. Only the series switch is sensitive to this coupling effect, which could be diminished through an increase in resistivity of the poly layer, together with a slightly modified layout that would reduce the overlap area.

3 CONCLUSION

The proposed interdigitated design of actuation and signal electrodes in ohmic RF-MEMS switches has proved to be a valid approach for achieving low-loss mechanical contacts with a standard surface micromachining technology. The measured insertion loss and isolation for the first prototype devices, in particular the shunt configuration, are compatible with multi-standard wireless RF-transceiver application specifications. A more even distribution of the electrostatic force across the plate is believed to result in uniform pressure for all contacts, yielding to lower contact resistance. Some improvements regarding both topology and technology have been identified for the next design cycle, especially regarding the series configuration. The extracted lumped element equivalent circuits have shown good agreement between measured and simulated s-parameters up to 13 GHz, and will provide the necessary tool for accurate RF circuit design.

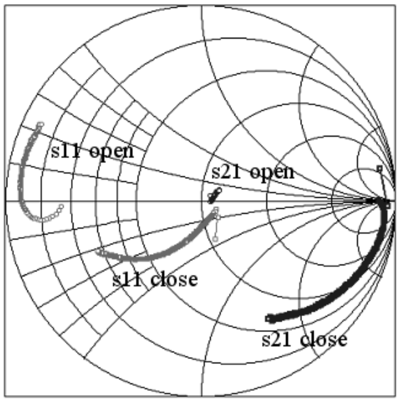

Figure 5: Open and close state frequency-domain s-parameters compared for the shunt switch (F=0.5-13.5 GHz).

4 ACKNOWLEDGEMENTS

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REFERENCES

[1] E.R. Brown, ”RF-MEMS Switches for Reconfigurable Integrated Circuits,” IEEE Trans. MTT, Vol.46, pp.1868-1880, Nov. 1998.

[2] J.B. Muldavin, G.M. Rebeiz, ”High-Isolation CPW MEMS Shunt Switches - Part 1: Modeling,” IEEE Trans. Microwave Theory Tech., Vol.48, pp.1045-1052, June 2000.

[3] A. Pothier, et Al., ”Low Loss Ohmic Switches For RF Frequency Applications,” 32nd Eu. Microwave Conf. Proc., Milan, IT, 23-27 Sept. 2002, pp.805-808.

[4] F. Giacomozzi, B. Margesin, L. Ferrario, V. Guarnieri, M. Zen, ”Micromachined Switches: Realization and Test,” Proc. 3rd MEMSWAVE Workshop, Heraklion, Greece, 26-28 June 2002.

[5] G. Dambrine, A. Cappy, F. Heliodore, E. Playez, ”A New Method for Determining the FET Small-Signal Equivalent Circuit,” IEEE Trans. Microwave Theory Tech., Vol.36, pp.1151-1159, July 1988.

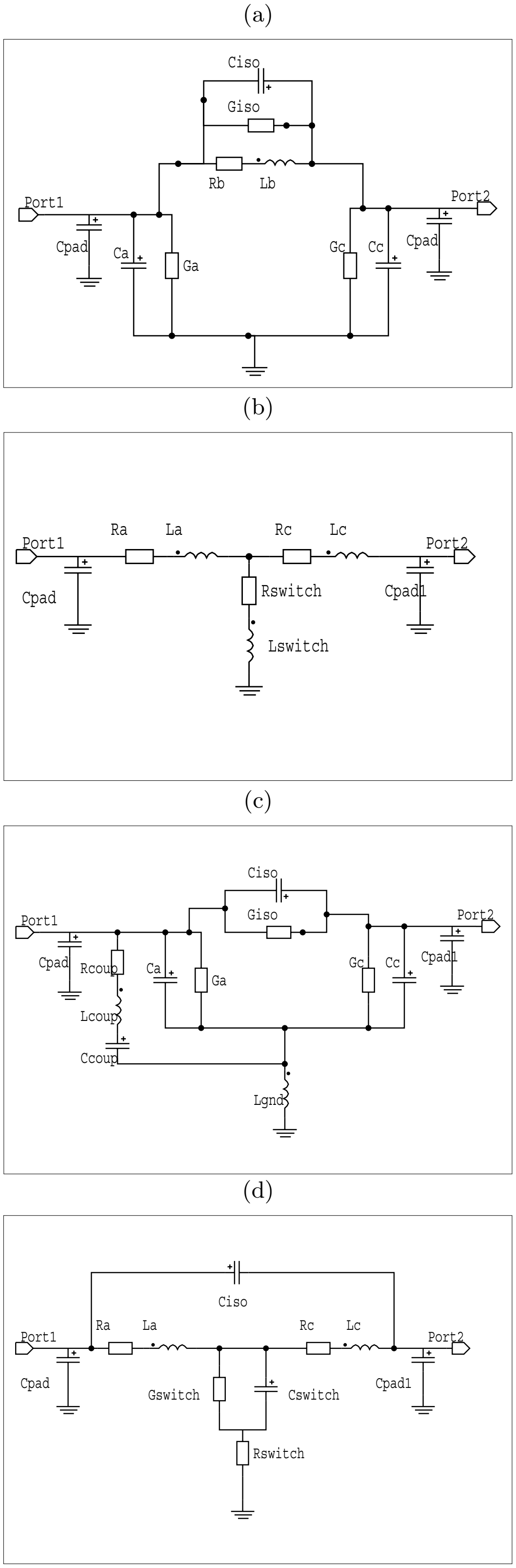

Figure 6: Extracted equivalent circuits: shunt switch up-state (a) and down-state (b); series switch up-state (c) and down-state (d).

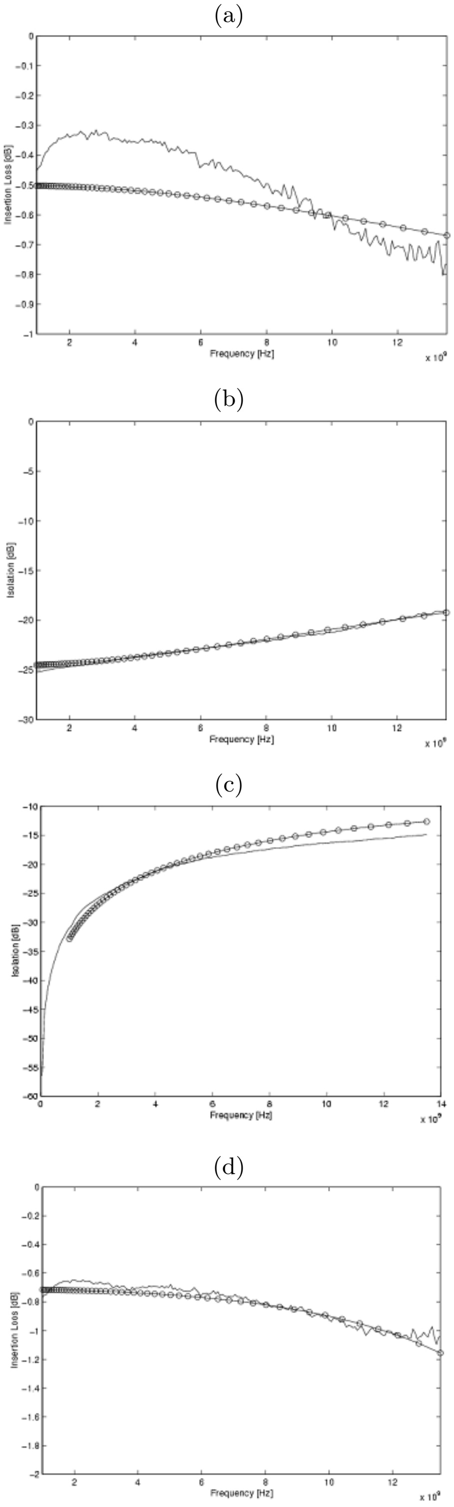

Figure 7: Measured (dots) and simulated (lines) s-parameters: shunt-switch insertion loss (a) and isolation (b); series-switch isolation (c) and insertion loss (d).