Compact thin-film packaged RF-MEMS switched capacitors

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***Abstract*—This paper presents the design, the realization and the measurement of a thin-film packaged RF-MEMS switched capacitors. Packaging is included in microelectronics fabrication process, with Silicon Nitride thin film. The capacitors are actuated by deflecting thin gold metal membranes towards the package dielectric, increasing the capacitance by a factor 2.3. The device size, including its packaging, is $50 \times 40 \mu m^2$. Pull-in and release voltages have less than 5V variation between 20°C and 85°C. The device has been tested with 20 dBm applied power and shows no sensitivity to incident power.**

***Index Terms*—Microelectromechanical systems, Package, RF-MEMS, Switches.**

I. Introduction

Reconfigurable devices RF components are more and more needed to deal with the ever-increasing demand for wireless data access. With the growing number of telecommunication standards, reconfigurable and tunable front ends are needed to limit the complexity of radio front ends. Switched RF-MEMS capacitors are among the serious candidates to realize this function thanks to their low losses, high linearity and very low power consumption compared to semiconductors [1].

Single RF MEMS devices can be combined into pseudo digital arrays of switched capacitors, with combinations resulting in well-defined step variations with high linearity and low loss. Other technologies, like series combination of stacked gate MOS transistors switches with fixed capacitors can be used for the same purpose. These semiconductor technologies offer moderate Q_s, but they can be made at very low cost, and are very easy to integrate in PC-board RF-circuits.

Indeed, considerations like cost, size, and easiness of integration are critical to the success of RF-MEMS technology. In particular, specific MEMS packaging has been one of the main roadblock against rapid and successful adoption of this technology.

Hermetic wafer-to-wafer bonding with glass-frit intermediate bond layer has successfully been used on commercial switches, but the thickness and profile of the resulting components make them difficult to integrate as surface-mounted elements. Moreover, these packaging techniques are very specific to MEMS and are difficult to insert in low cost CMOS fabrication process flow [2], [3].

Low processing effort and MEMS-unspecific packaging techniques are of high interest for the progress of this technology. There have been several efforts in the past towards the development of low cost, low profile thin film packaging. The idea is to use thin film processing steps for building dielectric shells above micro-electromechanical parts. Most proposed concepts in RF-MEMS stem from early work presented in [4], and have been further developed in [5]–[7], on various ohmic contact and capacitive RF-MEMS structures.

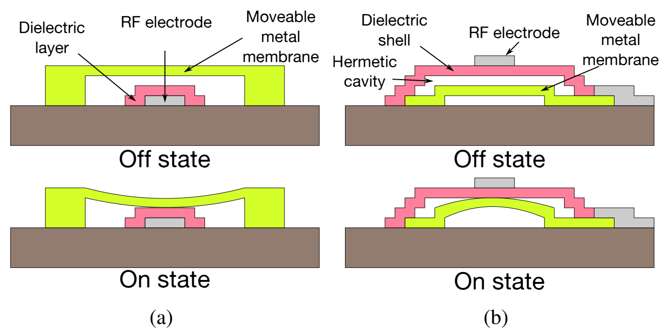


Figure 1. Operating principle of a conventional RF-MEMS capacitive switch (a) and proposed switched capacitor (b).

The structures presented in this paper are using miniature RF-MEMS capacitive structures [8]–[10], integrated into silicon nitride dielectric shells.

The compactness of the proposed components reduces sensitivity to temperature variations and will permits the integration of compact switched capacitors arrays.

II. Fabrication

A cross section of the proposed switched capacitor is shown in Fig. 1 along with a sketch of a conventional capacitive switch. In the proposed design, the RF signal electrode is standing above the deflectable metal membrane, and the dielectric layer is also used as a protective shell for the structure.

The processing steps are shown in Fig. 2. Switched capacitors have been fabricated on 400 µm thick silicon substrate, on which a 500 nm thick thermally grown SiO_2 on both sides.

Processing starts with the deposition and patterning of a first 300 nm thick sacrificial layer (Fig. 2a). Next, a 5 nm/400 nm Ti/Au membrane metal, with tensile stress, is evaporated and

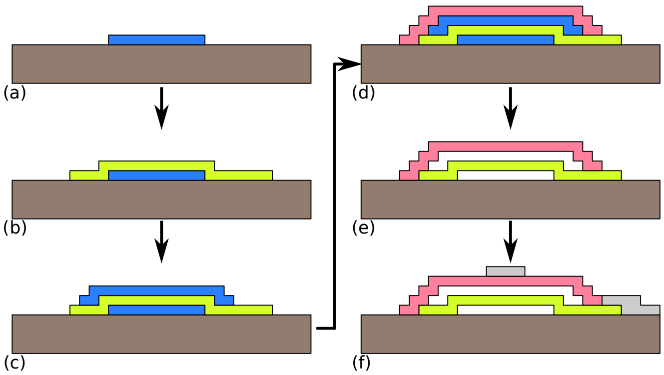
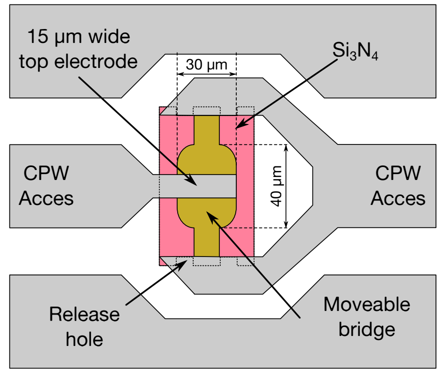


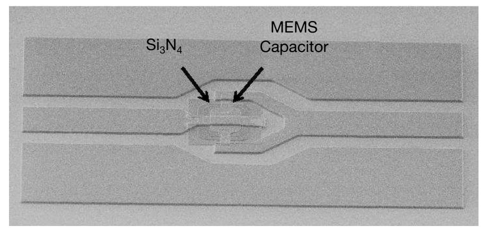
Figure 2. Fabrication steps of the switched capacitor.

Table I
SWITCHED CAPACITOR CHARACTERISTICS.

Beam length l	40 µm
Beam width w	30 µm
Pull-in voltage V_p	25 V (Meas.) / 29 V (Sim.)
Release voltage V_r	17 V (Meas.)
Mechanical resonance frequency	1.01 MHz (Sim.)
Switching times @ $1.5V_p$	384 ns (Sim.)
On-state capacitance	53 fF (Meas.)
Off-state capacitance	23 fF (Meas.) / 20 fF (Sim.)



(a)



(b)

Figure 3. Top view (a) and SEM (b) picture of a fabricated switched capacitor. The released capacitor cannot be seen on the SEM picture since it is covered by the dielectric shell.

patterned. Then a second 300 nm thick sacrificial layer is deposited and patterned (Fig. 2b and c).

A 500 nm thick Si_3N_4 layer is then deposited on top of the previous layers and the good conformal properties of the PECVD deposition techniques allowing maintaining good rigidity of the structure (Fig. 2d).

Small holes have been etched on the side of the dielectric shells to permit the release of the structure. After the sacrificial layers have been etched away, the devices are dried in a critical point drying system.

The last metal layer is 1.5 µm thick low-stress Al layer. This final layer closes release holes and thus finalizes the process of the switch. This metal layer also allows us to realize the top electrode and the CPW lines used for the switch (Fig. 2f). The volume of the fabricated cavities is about 1.5 pL, which is extremely small compared to other packaging techniques for RF-MEMS.

The switch dimensions are given in Fig. 3. The active area is only $40 \times 50\,\mu m^2$, including package. The moveable beam is 40 µm long by 30 µm wide. FEM and analytical [1] computed characteristics are summarized in Table I.

The devices have been simulated using ADS, and an equivalent scheme has been fitted to measurements.

III. MEASUREMENTS

The measured S-parameters are shown in Fig. 4 along with equivalent scheme modeling. No de-embedding has been performed on the presented measurements, and the presented results include aluminum pads to RF probe loss, and access pads substrate losses. The silicon resistivity adds a significant amount of loss at the access, and this phenomenon has been fitted using conventional CMOS access model.

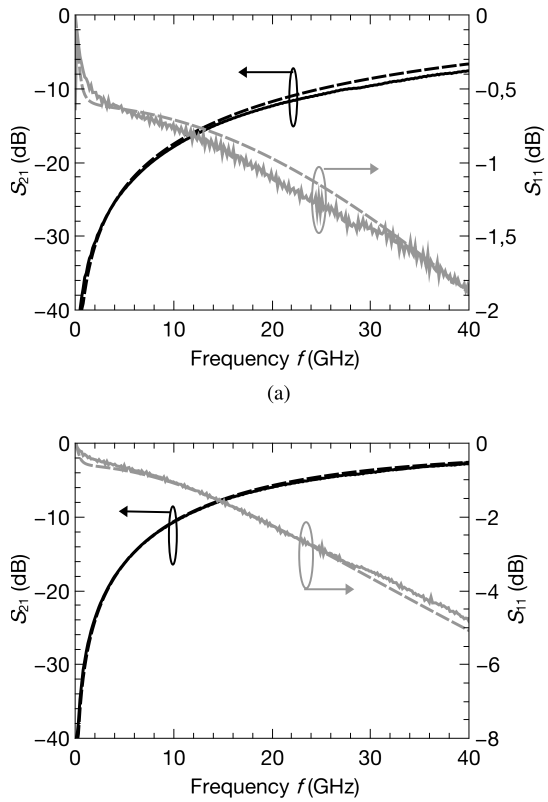
The probe to contact pads resistance could not be completely de-embedded and the actual series resistance of the switched capacitance was difficult to extract. Therefore, the capacitor Q could not be extracted accurately. However, the 1.5 µm thick metal Aluminum top layer strongly reduces ohmic loss compared to previously published designs [8]–[10]. Also, because of the small size of the device, no inductor in series was needed to model the capacitor up to 40 GHz (Fig. 5).

The devices have been biased using 1 kHz bipolar square waveform. When the bias voltage is applied, the extracted capacitance is 53 fF and when the bias voltage is removed, the capacitance value goes back to 23 fF, which is in good agreement with ADS Momentum simulations (Table I, 20 fF). The corresponding contrast is 2.3. The on state capacitance could not be predicted accurately by EM simulation because of the roughness of the dielectric layer.

The measured pull-in voltage is 25 V, in good agreement with analytical computation [1] (Table I, 29 V), and the release voltage is 17 V.

The pull-in and release voltages have been measured has function of the temperature and are reported Fig. 6. Because of the small size of the device, the temperature dependence is quite low between 20 and 85 °C. It is noteworthy that the temperature dependence comes both from the shell and the beam deformations.

The influence of the incident power is shown Fig. 7 for the two states. One can note the power does not lead to a variation of the transmission coefficient, showing that the



(a)

(b)

Figure 4. Measured (solid line) and equivalent scheme (dashed line) responses.

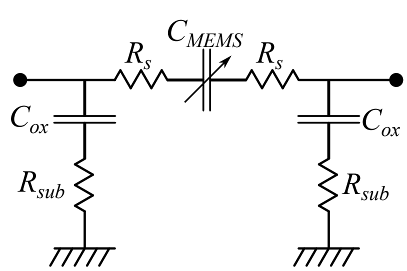


Figure 5. Equivalent scheme of the switched capacitor. C_{ox} = 0.3 pF, R_s = 2Ω, R_{sub} = 1.4 kΩ. C_{MEMS} is 53 fF in the on-state and 23 fF in the off-state.

capacitance is insensitive to the power up to 20 dBm. In the present configuration, the capacitance is in series and the incident power generates maximum voltage across the device.

IV. Conclusion

A novel switched capacitor has been designed, fabricated and tested. Extremely small packaging has been integrated in the fabrication process, using standard microelectronics processing steps. The capacitor can be switched between 23 and 53 fF, and can be easily put into arrays of devices in order to obtain compact digital-like variable capacitors. The measured capacitance contrast is 2.3 but it can be easily increased by adding a third electrode to obtain a tri-plate configuration as proposed in [10]. The devices are using relatively thick metals, and will permit the fabrication of very

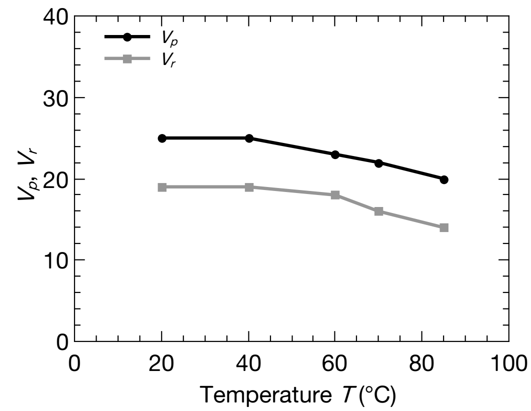


Figure 6. Pull-in voltage V_p and release voltage V_r as a function of temperature.

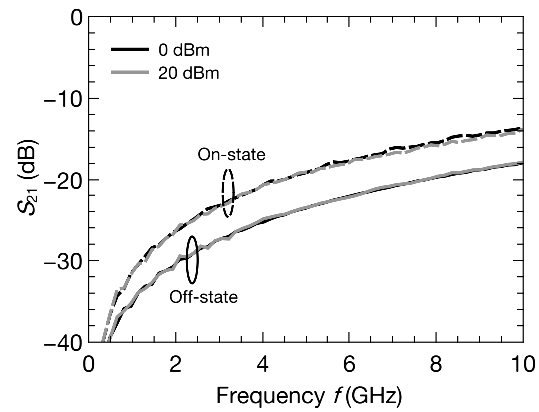


Figure 7. Measured transmission coefficient for two different incident powers (0 dBm and 20 dBm) for the off-state and the on-state.

low loss, zero level packaged RF-MEMS variable capacitors arrays.

Acknowledgment

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