Reliability test of a RF MEMS varactor based on a double actuation mechanism

A. Cazzorla, P. Farinelli, R. Sorrentino, B. Margesin

Abstract

This paper presents the design and reliability tests of a novel micro-electro mechanical varactor based on a double actuation mechanism allowing for overall capacitive ratio $C_0$ of 5.2 and continuous capacitive ratio $C_r$ of 2.6. The device has been modeled in ANSYS® multiphysics environment and manufactured by using the 8-masks FBK-irst RF MEMS process. The performance was tested on 10 samples showing good mechanical reproducibility and negligible capacitance ratios variation ($C_0 = 5.2 \pm 5\%$, $C_r = 2.6 \pm 4\%$). Self-biasing tests have been performed by applying an equivalent $V_{bias}$ on the RF central conductor, showing an insignificant capacitance ratio variation up to 13.5 $V_{bias}$. Finally, cycling test was performed on the DUT up to $10^8$ cycles, showing negligible variation of the capacitance.

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1. Introduction

In recent years, the growth of novel wireless communications standards has introduced new challenges in the design of the transceiver hardware. Low power consumption, and high linearity are the most important requirements that every component has to satisfy in order to achieve high performance wireless systems. RF MEMS technology has already demonstrated its high potentialities as an alternative to solid-state technology, thanks to the nearly zero power consumption, wide-band operation and high-Q, from DC up to mm-wave frequencies [1]. RF MEMS varactors are an attractive solution to replace conventional tunable capacitors in several applications [2–4], since they allow for continuous tuning of the signal, enabling fine-tuning operation with a very low biasing network complexity.

The dynamic range of conventional parallel plate MEMS capacitors is governed by pull-in instability. Theoretically, the latter limits the continuous tunability range of MEMS capacitors to ~50%, before membrane snap-down. In recent years, to overcome this theoretical limit, various approaches have been proposed. In [5], a tunable capacitor based on zipping actuation mechanism with a tuning range of 3:1, was developed. Dual gap parallel plate topology with a tuning range of 6:2:1 was presented in [6]. However, a number of serious reliability and cost issues remain unanswered for MEMS varactors. First, operational reliability, i.e. the ability of devices to work over the whole lifetime, and robustness to process parameter variations or thermal stability, are key issues in RF MEMS design [7]. Second, the power handling capability [8], i.e. the ability of the devices to handle medium-high RF power signal (1 W–10 W) without temporary or permanent failures, is an important requirement for using the component in matching networks in TxRx RF modules or low noise RF Voltage Controlled Oscillators (VCOs).

This paper presents the modeling and reliability testing of a novel micro-electro mechanical varactor showing a theoretical overall capacitive ratio ($C_0$) of 6 and continuous tuning of 2.6. The device has been manufactured by using the 8-masks FBK [9] RF MEMS process, without increasing the MEMS manufacturing complexity and costs. Self-biasing and cycling tests are presented.

2. Design and modeling

2.1. Principle of operation

The proposed MEMS varactor consists of a gold membrane (1250 µm long and 200 µm wide) mechanically anchored at the CPW ground (by six identical lever springs, long $L_a$ and wide $w_a$) and at the substrate (Fig. 1).

Four identical lever springs (long $L_a$ and wide $w_a$) were designed in the central part of the membrane to prevent the membrane snap-down as explained in the following. The movable gold membrane is 2 µm thick, locally reinforced with a second deposition of 3.5 µm thick gold layer ensuring high beam flatness. The proposed approach is based on a double actuation mechanism. To this purpose, the DC electrodes have been split into two separate electrodes, called L.E. (lateral electrodes) and C.E. (central electrodes).

When the device is in its “initial state” (Fig. 2a), the residual gap ($g_0$) between movable membrane and RF electrode is 2.7 µm.

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When the L.E. are polarized, the bridge lateral parts snap on the L.E., reducing the gap from \( g_0 \) to \( g_{up} \) ("up-state", Fig. 2b). During this first actuation, the mechanical bonds in the center inhibit the snap-down of the membrane central part, which remains about 1.1 \( \mu \)m (\( g_{up} \)) suspended above the RF line. Afterwards, the central electrodes (C.E.) are polarized to continuously reduce the gap up to \( g_{down} \) ("down-state", Fig. 2c) allowing for a continuous capacitance variation. Mechanical stoppers were integrated in the actuation pads to avoid the contact between movable membrane and the dielectric-less actuation electrodes. They are made by the stuck of the thin metal and insulating layers available in the standard process [9], such as polysilicon, TiN/Ti/Al/Ti/TiN multi-metal, and gold for a total height of about 1.2 \( \mu \)m.

### 2.2. Spring lever design

In order to prevent the complete membrane snap down during the first actuation, the lever springs in the central part of the membrane were designed to be stiffer (in Fig. 3, \( k_b > k_a \)) than the ones in the lateral part of the membrane.

Fig. 1. Manufactured prototype of proposed MEMS varactor.

Fig. 2. Cross-section of the MEMS varactor: a) Initial state (0 V applied on DC electrodes); b) Up-state (L.E. = ON and C.E. = OFF); c) Down-state (L.E. = ON and C.E. = ON).

Fig. 3. Top view of the simplified mechanical model of the MEMS varactor based on double actuation mechanism.

Fig. 4. Spring constant as function of the lever spring length in the membrane central part (red line) and lateral part (blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. FEM modeling: a) anchor-to-anchor delta displacement (\( \Delta - z \)) as function of the residual stress; b) delta displacement (\( \Delta - z \)) as function of the applied voltage on DC electrodes.

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The spring constant was calculated as a function of the lever spring length by using equations reported in [1]. The result is shown in Fig. 4. The values $L_1 > 97 \mu m$ and $L_2 < 77 \mu m$ ensure that, during the first actuation, the complete snap down in the membrane central part is avoided.

Note that the analytical model does not account for the effect of the residual stress in the membrane.

2.3. FEM modeling

The varactor was modeled in the FEM ANSYS® multiphysics accounting for residual stresses and non-linear behavior of the lever springs at standard temperature ($T = 25^\circ C$). First, the static deflection of the movable membrane was analyzed, taking into account the initial deformation of the membrane due to residual stress. Fig. 5a shows the varactor anchor-to-anchor delta displacement ($\Delta z$), along z-axis, just after the release of the structure under different residual stress conditions ($\sigma = 30 \text{ MPa, } 60 \text{ MPa, } 80 \text{ MPa and } 100 \text{ MPa}$). The membrane shows low sensitivity to stress variations: the downward bending is about 170 nm and 370 nm for residual stresses in the gold layer of $\approx 30 \text{ MPa}$ and $30 \text{ MPa and } 100 \text{ MPa}$ respectively.

Then, by applying DC control voltage (up to 40 V) on the L.E., the initial gap ($g_0$) decreases up to $g_{gap} \approx 1.1 \mu m$. Note that, as in conventional parallel plate capacitor, after one third of the initial gap the membrane collapses due to the pull-in effect ($V_{pull-in} = 37.5 \text{ V}$). The complete membrane snap-down above the RF line is avoided thanks to additional mechanical bond in the central part of movable membrane. Then, by applying a DC signal (up to 60 V) on the C.E., the gap $g_{gap}$ is continuously decreased up to $g_{down} \approx 0.45 \mu m$ allowing for continuous and high tuning of the MEMS capacitance (Fig. 5b). In this case the movable membrane touches the mechanical stoppers (placed close to the central electrodes) before starting pull-in behavior (DC signal on central electrodes $\approx 30 \text{ V}$). Then by increasing the voltage, the membrane continues to displace assuming a zipping motion.

The resulting varactor displacement along z-axis, in the three-state mode, is reported in Fig. 6.

The varactor was modeled and designed (by using ANSYS® HFSS) in shunt configuration with respect to a 2 mm long CPW line, in the $0-30 \text{ GHz}$ frequency range (Fig. 7a).

The equivalent circuit (Fig. 7b) was used to fit the simulation results and extract the theoretical capacitance values of the device. Table 1 shows the comparison between simulated and measured RLC parameters. In its initial state, the device presents a shunt capacitance $C_{var} = 102.5 \text{ fF}$. In its up-state and down-state, the simulated shunt capacitances are 233.5 fF and 616.6 fF respectively. This results in a theoretical non-continuous capacitive ratio $C_r$ of about 6 and in a continuous tuning of 2.6.

3. Fabrication

The varactors have been manufactured by FBK using their standard RF MEMS process. The process is based on the combination of elements of the planar technology, as used for CMOS devices, with surface micromachining techniques. The technology is capable to produce complex RF circuits including MEMS switches and high quality passive components in high quantities and at a low cost. The principal structural elements are a 2 $\mu m$ thick galvanic gold layer that provide the high conductive transmission lines and, in combination with the sacrificial layer, the mobile suspended structures used to build the electrostatically actuated switches (Fig. 8).

Designed to be able to build both, ohmic type and capacitive type switches, the 8-mask process is capable to build a wide variety of electrostatically actuated structures and allows for design strategies that reduce dielectric charging.

A detailed description of the fabrication process can be found in [9]. The devices presented in this paper have been built within a Multi Project Wafer run by using the standard features of the process.

![Fig. 6. FEM modeling: membrane displacement (µm) in initial state, up-state and down-state.](Image)

![Fig. 7. FEM modeling: a) Single die, b) Varactor equivalent circuit. C_{var} is the varactor capacitance. L_s and R_s are the membrane inductance and resistance. C_{sub} and R_{sub} are the parasitic capacitance and the resistivity of the substrate.](Image)

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<th>Measured</th>
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<td>115 fF</td>
</tr>
<tr>
<td>$C_{var}$ (Up-state)</td>
<td>233 fF</td>
<td>225 fF</td>
</tr>
<tr>
<td>$C_{var}$ (Down-state)</td>
<td>616 fF</td>
<td>600 fF</td>
</tr>
<tr>
<td>$R_s$</td>
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<td>0.5 Ω</td>
</tr>
<tr>
<td>$L_s$</td>
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<td>49 nH</td>
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<td>$C_r$</td>
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</tr>
<tr>
<td>$C_r^*$</td>
<td>2.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

| Table 1. Comparison between measured and simulated RLC parameters. |
4. Experimental results

4.1. RF performance

On-wafer RF characterization was performed at standard temperature condition (T = 25 °C), by using Agilent N5230A VNA, CPW probes and SOLT calibration in the 0–30 GHz frequency band.

Return loss as a function of the applied voltage is shown in Fig. 9. As expected, the varactor presents two different continuous tuning ranges: the first one, before the pull-in (measured V_{pull-in} = 35 V), allows a continuous tuning ratio of about 1.6; the second one, after the pull-in (when L.E. = 40 V and 0 V ≤ C.E. ≤ 60 V), allows a continuous variation of the signal up to 2.6.

The comparison between simulated and measured capacitances (C_{var}) as a function of the applied voltage (when it increases or it decreases) is shown in Fig. 10 and summarized in Table 1. The results are in a good agreement with the simulations, showing a measured non-continuous capacitive ratio (C_r) of 5.2 and a continuous capacitive ratio (C_r*) of 2.6.

Note that the capacitance–voltage (C-V) curves for increasing and decreasing voltages overlap in the right part of the graph (Fig. 10, i.e. when the voltage is applied on the C.E.) while present a hysteresis on the left part of the graph. This is due to the fact that no pull-in takes place when C.E. are polarized, while a pull-in and pull-out voltages of 35 V and 29 V respectively have been recorded on the L.E.

In addition the performance has been verified on ten samples. Measured pull-in, pull-out voltages as well as the capacitive ratios for ten samples are reported in Table 2.

4.2. Cycling test

In order to verify the pull-in/pull-out voltage shift and the capacitance variation after large number of actuations, some samples were cycled up to 100 million cycles.

In the first case, the test was performed by using the Agilent 33120a (plus commercial DC–DC converter) function generator, generating a 1 KHz, 50% duty cycle, square waveform with a peak value equal to the measured pull-in voltage of the sample which was applied at the lateral electrodes (L.E.). At step size of 10 million cycles, voltage pull-in and pull-out were measured and results are shown in Fig. 11. A negligible variation of the voltage pull-in and pull-out values was measured resulting in a voltage shift of about +4 V up to 100 million cycles.

Then the cycling test was repeated using the same duty cycle, square waveform with a peak value equal to 60 V applied at the C.E. while the L.E. were set to 55 V throughout the needed time of the test. Electric and mechanical parameters did not exhibit significant changes up to 100 million cycles, as shown in Fig. 12. Moreover the capacitance (C_{var}) as function of the applied voltage was measured, after 100 million of cycles, and it is shown in Fig. 10. A negligible variation of few tens of

<table>
<thead>
<tr>
<th>#</th>
<th>C_r</th>
<th>C_r*</th>
<th>V_{pull-in}</th>
<th>V_{pull-out}</th>
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<tr>
<td>1</td>
<td>5.5</td>
<td>2.6</td>
<td>36</td>
<td>27</td>
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<td>5.2</td>
<td>2.7</td>
<td>36</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 2: Repeatability of 10 sample devices.
ff was recorded resulting in a variation of about 3% and 1% for the non-continuous and continuous capacitive ratio, respectively.

4.3. Power handling capability

The test was performed to evaluate the self-biasing effect [10]. The latter is related to the equivalent voltage, usually referred to as root mean square (RMS) voltage, provided by the power of the propagating RF signal. Table 3 shows the measured capacitance values and capacitive ratios as function of the input power and root mean square voltages. The device shows negligible variation in the continuous capacitive ratio ($C_r$) up to 35 dBm, (it moves from 2.6 at 3 dBm to 2.45 at 35 dBm). For higher input powers, the device collapses onto the RF line; however, up to 40 dBm, the device can operate as a classical MEMS capacitive switch. In this case, the non-continuous capacitive ratio ($C_i$) is about 10, since the capacitance increases thanks to the membrane mechanical relaxation onto the fixed electrode.

The proposed experimental results did not account for the dissipated power of the propagating RF signal, which can increase the temperature of the movable membrane, relaxing the stress and decreasing the biasing voltage on DC electrodes.

5. Conclusions

In this paper the modeling and reliability tests of a novel micro-electro mechanical varactor were presented. The tunable capacitor is based on a double actuation mechanism allowing for an overall capacitive ratio of 5.2 and a continuous tuning of 2.6. The repeatability of the performance was tested on 10 sample devices resulting in a negligible capacitance ratio variation. Cycling test has shown a marginal variation of the capacitance and voltage pull-in/pull-out values up to 10⁸ cycles. Finally, the self-biasing effect was evaluated on the DUT showing that the continuous tuning range is not significantly reduced even when applying RF amplitude up to 13.5 $V_{\text{rms}}$.

Table 3

<table>
<thead>
<tr>
<th>$P_i$ [dBm]</th>
<th>$V_{\text{rms}}$ [V]</th>
<th>$C_{\text{var}}$ a [fF]</th>
<th>$C_{\text{var}}$ b [fF]</th>
<th>$C_{\text{var}}$ c [fF]</th>
<th>$C_r$</th>
<th>$C_i$</th>
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<td>3 dBm</td>
<td>0.3</td>
<td>115</td>
<td>225</td>
<td>600</td>
<td>5.2</td>
<td>2.6</td>
</tr>
<tr>
<td>27 dBm</td>
<td>5.1</td>
<td>115</td>
<td>225</td>
<td>600</td>
<td>5.2</td>
<td>2.6</td>
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<td>115</td>
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<td>35 dBm</td>
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<td>304</td>
<td>750</td>
<td>6.5</td>
<td>2.45</td>
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<tr>
<td>37 dBm</td>
<td>16</td>
<td>116</td>
<td>–</td>
<td>832</td>
<td>7.2</td>
<td>–</td>
</tr>
<tr>
<td>40 dBm</td>
<td>22</td>
<td>116</td>
<td>–</td>
<td>1200</td>
<td>10</td>
<td>–</td>
</tr>
</tbody>
</table>

a Initial state.

b Up-state.

c Down-state.

Fig. 11. Pull-in/pull-out voltages for samples #2 (blue diamond), #6 (red square) and #9 (black circle) as function of the number of cycles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. Capacitance values as a function of the number of cycles.

References