Capacitance Tuning Behavior of a BiCMOS Embedded RF-MEMS Switch

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Abstract. The capacitance tuning behavior of a BiCMOS embedded RF-MEMS switch is investigated. The novel switch electrode configuration allows precisely obtaining intermediate capacitance values between the off-state (Coff) and on-state (Con) capacitances under specific AC signal conditions. The stable capacitance tunability is demonstrated by both optical and electrical methods. For AC amplitudes up to 400mV, capacitance tuning with a ratio of 1:10 is achieved without any pull-in effect. The results show that the RF-MEMS switch can be used as a tunable capacitor for mm-wave applications.

Index Terms: Embedded MEMS, RF-MEMS switch, mm-wave circuits, varactor, tunable capacitor.

1. Introduction

Latest developments in RF-MEMS technology have opened the way for achieving high performance and IC-integrated MEM devices/systems, especially RF-MEMS switches and tunable capacitors. RF-MEMS components are considered as one of the key components for the development of the next generation multi/wide band communication systems [1, 2]. Many communication systems such as satellite communication or wireless local area networks (WLAN) require tunable components to have multi-band or wide-band operation [3]. P-N junction or inversion MOS types of varactors are the main components in BiCMOS technologies to achieve capacitance tuning with limited capacitance ratios. However, the quality factors of such devices are limited especially for mm-wave frequency ranges. RF-MEMS tunable capacitors are used in voltage-controlled oscillators, matching networks and tunable filters and provide a wide capacitance tuning and a high quality factor, especially for the frequency below 10GHz [4, 5]. There is a strong need of a tunable capacitor in mm-wave frequency range which has a high capacitance ratio and a high quality factor. Recently, a BiCMOS embedded RF-MEMS switch was demonstrated with an excellent performance and very good reliability [6, 7]. The capacitive-type RF-MEMS switch shown in Fig. 1 provides a C_{off} /C_{on} ratio larger than 1:10 and is therefore a potential candidate for using it as a tunable capacitor especially due to the electrode configuration which provides a continues control of the movable membrane displacement without any pull-in effect.

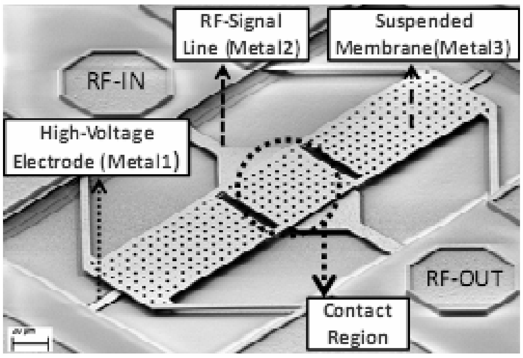

Fig. 1. BiCMOS embedded RF-MEMS switch [6].

In this work, the mechanical and electrical performance of a BiCMOS embedded RF-MEMS switch which is used as a tunable capacitor have been demonstrated. The electrode configuration allows to precisely achieving the intermediate capacitance values between the off-state (C_{off}) and the on-state (C_{on}) capacitances under specific AC signal conditions. The mechanical and the electrical characteristics have been investigated by different methods to overcome the specific measurement effects. Measurement results show that the RF-MEMS switch can be used as a tunable capacitor with a C_{off} /C_{on} capacitance ratio of 1:10. The advantage of electrode configuration which provides a mechanical movement without any pull-in effect is detailed.

RF power handling performance of the tunable capacitor is also analyzed.

2. Technology

The fully embedded RF-MEMS switch has been built between the Metal2 (M2) and Metal3 (M3) of BEOL metallization of IHP's 0.25µm SG25H1 BiCMOS process (Fig. 1) [5]. The specific RF-MEMS switch consists of M1 used as high voltage electrodes for electrostatic actuation and the stress-compensated M3 stack which is used as the movable membrane (Fig. 2). The original RF-MEMS switch process is slightly modified and the initial gap between M3 and M2 is lowered from 1300nm to 900nm to have a better tuning capability. The Con/Coff ratio is higher than 1:10 and makes the RF-MEMS switch feasible to use it as a tunable capacitor with a wide and continues tuning range.

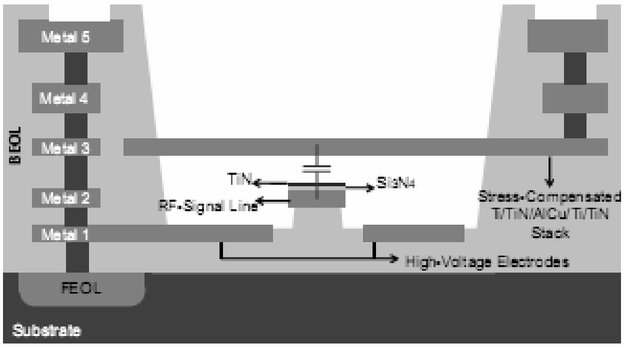

Fig. 2. Cross-section view of RF-MEMS Varactor.

3. RF-MEMS Tunable Capacitor

The nonlinear behavior of the electrostatic actuation with the characteristic pull-in effect is one of the main reasons which limit the tuning range of MEMS tunable capacitors. The equation (1) gives the relation between the applied voltage and the changing gap where the A is the area, go is the initial gap and the g is the displacement [8].

$$\frac{\varepsilon_0 \cdot \varepsilon_r \cdot A \cdot U^2}{2 \cdot g^2} = k \cdot (g_0 - g) \qquad (1)$$

After the voltage pull-in voltage (U_{pi}) is reached i becomes equal to (2) and pull-in occurs. At this voltage the membrane suddenly moves down to the contact and canno be held in a stable position [8]. By the help of (1) and (2), it can be shown that the displacement can be controlled only for the first 1/3 of the initial distance between the movable membrane and the high-voltage electrodes [8]. This phenomenon limits capacitance tuning of electrostatic actuated MEMS varactors because the higher capacitance values are achieved when the membrane is close to the contact.

$$U_{pi} = \sqrt{\frac{8 \cdot k}{27 \cdot \varepsilon_0 \cdot \varepsilon_r \cdot A}} \cdot g_0^3 \qquad (2)$$

The BiCMOS embedded RF-MEMS switch in this study has a specific electrode configuration. The details are given in Fig. 4. As can be seen from

Fig. 4, the high voltage electrodes (M1) are in a lower position than the contact level (M2).

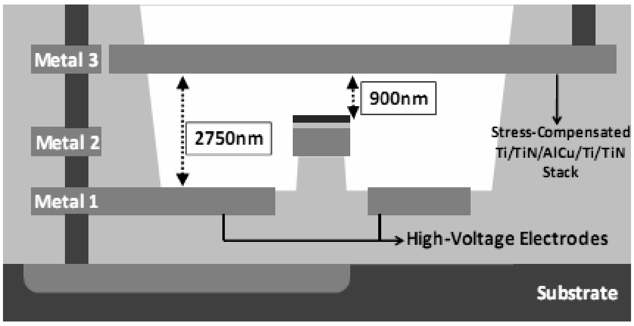

Fig. 3. Detailed cross-section of the RF-MEMS varactor.

Different principles have already been proposed in literature to prevent from nonlinearities of the pull-in effect such as three-plate configuration or separation of actuation electrodes and signal-line [9, 10]. The present RF-MEMS varactor is based on the second principle and therefore is insensitive to the nonlinear characteristic of electrostatic actuation. The initial distance between the membrane (M3 and the electrode (M1) is 2750nm while the gap between th signal line (M2) and the membrane (M3) is 900nm. Th movable membrane can be controlled in every position between M3 and M2. The specific electrode configuration allows using the MEMS switch as a MEMS variable capacitor. Furthermore, the electric field occurs only from the sides of the movable membrane (Fig. 3) which also helps to prevent from pull-in effect.

Although the standalone DC actuation voltage does no cause any pull-in effect, the AC signal on the signal lin (M2) can also affect the mechanics of membrane and pull-in can occur due to the high amplitude of AC signal [11]. The membrane is very sensitive to the AC signal amplitude when it is too close to signal line (M2). This effect obviously limits the power handling of the MEMS structur when it considered to be used as a variable capacitor Furthermore, precise capacitance measurements require specific voltage level which influences the C-V behavio during measurements. Therefore both optical and electrica measurements have been performed to distinguish between different effects which can result with pull-in of the switch.

4. Experimental Results

To analyze the variable capacitor performance of the switch, optical and electrical measurements have been done The displacement of the membrane by applied voltage has extracted using optical methods while the electrical method has provided the capacitance versus applied voltage curve Finally, the results from different methods have been correlated.

A. Optical Measurements

Optical measurements have been performed to investigate the deflection of the membrane with respect to the applied voltage which is related to the contac capacitance between M2 and M3. In comparison to electrical measurements, it provides a membrane deflection without any applied signal on M2 and therefore prevent from the mentioned pull-in effect which can occur due to high amplitude of AC signal on the signal line (M2). The Laser-Doppler-Vibrometer MSA-500 from Polytec® (LDV has been used to measure the maximum deflection in the middle of the contact area with respect to the actuation voltage which has been changed with 100mV steps between 13V to 20V. The result of the displacement-voltag behavior is shown in Fig. 4.

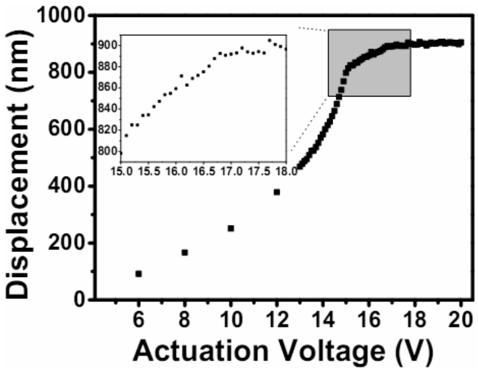

Fig. 4. LDV measurement of RF-MEMS varactor: Displacement versus actuation voltage. Every point in figure shows a measurement point.

The total displacement is approximately 900nm with a required voltage of 14-18V (Fig. 4). 100mV voltage steps are applied between 13V to 20V to better extracting the tuning region. All the measurement points show the stable membrane position which approves that the MEMS switch can be easily controlled with 100mV voltage steps.

B. Electrical Measurements

Although the optical results show that the mechanics of the RF-MEMS switch is suitable to use it as a variable capacitor, appropriate electrical performance is also necessary. Therefore, the contact capacitance measurements between M2 and M3 have been performed using Agilent® 4294A Precision

Impedance Analyzer. The measurement frequency of the AC signal was taken as 100 kHz to measure the capacitance. AC signal is applied to M2, resulting in an influence on the mechanical behavior of the membrane. If the amplitude of this signal is too high, this can also affect the mechanical behavior of the switch.

Therefore, the AC signal amplitude was chosen as 100mV not to affect the dynamics of the switch. The total capacitance from signal line (M2) to substrate without a suspended membrane (M3) has been removed from the total measured capacitance to extract the pure contact capacitance for both off and on states. A switch without any membrane was used to measure the coupling capacitance from signal line (M2) to substrate. The de-embedded contact capacitance between M2 and M3 is given in Fig. 5. The off-state and the on-state contact capacitances have been measured as 16fF and 165fF, respectively. Fig. 5 shows almost continues C-V curve for an AC voltage increment of 100mV. The intermediate capacitance values between off and on states have been achieved by applying 100mV actuation voltage steps. On the other hand, it is noted that such small amplitude (100mV) of the measurement signal has no effect on the mechanics of membrane. Under such low amplitude of AC signal, electrical measurements also provide acceptable variable capacitor performance.

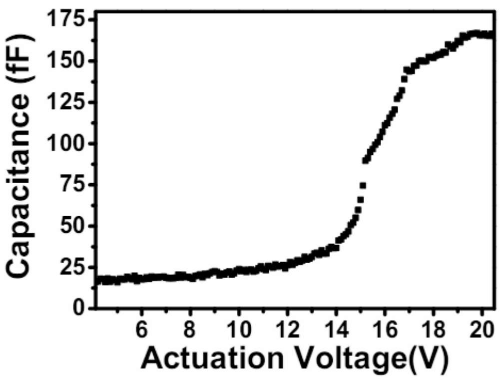

Fig. 5. De-embedded contact capacitance versus actuation voltage. Every point in figure shows a measurement point.

C. Nonlinear Movement

As illustrated in Fig. 6, there are three main different regions in case of the displacement-voltage and capacitance-voltage behavior (Fig. 6). The main reason for such behavior is the nonlinear movement of the membrane and the specific electrode configuration. The LDV with the scanning option has been used for better understanding the different effects on dynamic behavior. Following effects have been observed after detailed analyses of the dynamics: In region A, the whole membrane (the middle region and the side parts) moves down and at the end of region A, the sides stop to move. In region B, only the middle part moves down and the sides almost do not move. The first contact between M2 and M3 is achieved at the end of the region B. This can also be seen from the displacement curve because the displacement finishes at the end of region B. Region C helps to define the real contact and the final position of the membrane. In region C, there is no remarkable displacement but a significant capacitance increase can be observed.

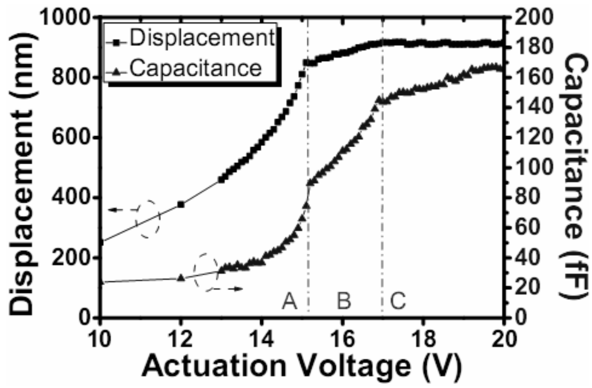

Fig. 6. Different regions of membrane movement. Every point in figure shows a measurement point.

5. RF Power Handling

As mentioned in previous parts, the amplitude of the AC signal on the signal line (M2) has a strong effect on the dynamics of the RF-MEMS switch if it is used as a variable capacitor. The capacitance measurements have been repeated using different AC signal amplitudes to define the maximum allowable amplitude that can be used on the RF line (M2). An AC signal with a frequency of 100kHz and amplitude values ranging from 100mV to 800mV has been used. Fig. 7 shows the C-V curve for different amplitudes of AC measurement signal. It is clearly seen that the increase of the amplitude results with a stronger pull-in effect. Up to 400mV, almost all the intermediate capacitance values can be achieved using 100mV actuation voltage steps but using 800mV amplitude of AC signal, the capacitance values between 50fF to 150fF cannot be achieved due to the strong pull-in effect (Fig. 7).

Table 1 summarizes the dependency of the C_{on}/C_{off} ratio and pull-in effect to AC signal amplitude. No real pull-in effect was observed for the AC signal amplitudes of 100mV, 200mV and 400mV. At 800mV amplitude of AC signal, strong pull-in effect was observed due to the high amplitude of the AC signal.

For the first three cases, the capacitance tunability is almost the same like in case of 100% tunability with capacitance ratio of 1:10 because there is no real pull-in effect. But in case of 800mV AC signal amplitute, the maximum tuning range reduces to 1:3.7 because the intermediate capacitance values between 50fF to 150fF cannot be achieved using 100mV actuation voltage steps. It is obvious that if the RF-MEMS switch wanted to be used as a variable capacitor with a 100mV actuation voltage steps, the AC signal amplitude on the signal line should be kept below 400mV to achieve a continues tuning range.

Such power levels are enough for most of the mm-wave SiGe applications. Another approach to handle more RF signal amplitude would also be using an actuation voltage steps smaller than 100mV.

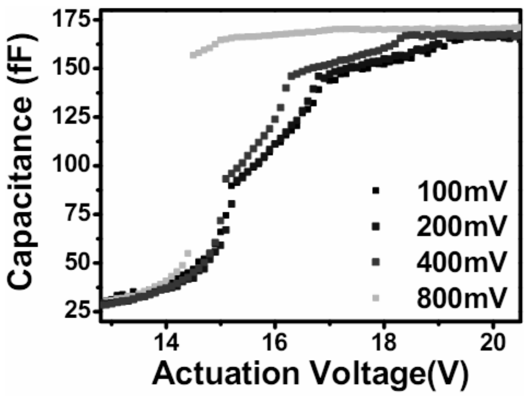

Fig. 7. De-embedded contact capacitance versus actuation voltage curves for different amplitudes of AC signal used for capacitance measurements. Every point shows a measurement point with an increment of 100mV.

Table 1. Dependency to AC signal amplitude

Umeas [mV]	Con/Coff	Pull-In Effect [V]
100	10.8	No Pull-in
200	10.9	No Pull-in
400	10.8	No Pull-in
800	11	~ 14.5

6. Conclusion

A BiCMOS embedded RF-MEMS switch has been used as tunable capacitor. The stable capacitance tunability has been demonstrated using electrical measurement supported by optical measurement to understand the effect of the AC signal amplitude. Up to 400mV AC signal amplitude, continues tuning ratio of 1:10 has achieved without any pull-in effect. A further increase of the AC signal amplitude leads to a strong pull-in effect and reduces the tuning ratio. The results show the feasible usage of RF-MEMS switch as a tunable capacitor for mm-wave applications.

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