Center-shift method for the characterization of
dielectric charging in RF MEMS capacitive switches

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\textbf{Abstract—} RF MEMS capacitive switches show great promise for use in wireless communication devices such as mobile phones, but for the successful application of these switches their reliability needs to be demonstrated. One of the main factors that limits the reliability is charge injection in the dielectric layer (SiN) which can cause irreversible stiction of the moving part of the switch.

We present a way to characterize charge injection. By stressing the dielectric with electric fields on the order of 1 MV/cm, we inject charge in the dielectric, and measure the effects it has on the \(CV\) curve. Instead of conventionally measuring the change of the pull-in voltage, the presented center shift method measures the change of the voltage at which the capacitance is minimal. This way, the measurement method does not influence the charge injected by the stress-voltage. Another advantage is that the measurement of the amount of injected charge is not influenced by changes in the width of the \(CV\) curve.

\textbf{Index Terms—} capacitive switch, charging, dielectric, reliability, RF MEMS.

\section{I. INTRODUCTION}
RF MEMS (Radio Frequency Micro-Electro-Mechanical Systems) capacitive switches show great potential for use in wireless communication devices such as mobile phones. This is due to the low loss, high linearity, good power handling and low power consumption of the switches [1]. Fig. 1 shows a schematic representation of an RF MEMS capacitive switch. The top electrode is suspended by (tiny) springs and can be pulled down by applying a voltage across the air gap between the two electrodes. Above a certain voltage, the balance between the attracting electrostatic force \(F_E\) and restoring spring force \(F_{spring}\) becomes unstable and the switch closes, which is marked by a sudden increase in the capacitance of the switch (Fig. 2). This voltage is called the pull-in voltage \(V_{pi}\). A dielectric layer prevents DC current flow. Once closed, the electric forces are much higher due to the shorter distance between the electrodes, and the switch will only open again if the voltage is lowered below the so-called pull-out voltage \(V_{po}\). \(V_{pi}\) and \(V_{po}\) can be found by measuring the hysteresis present in the capacitance-voltage curve of the switch (Fig. 2). Since the electrostatic force is proportional to the voltage squared, pull-in and pull-out occur for both positive and negative applied voltage, indicated in the figure by \(V_{pi}^{+}\), \(V_{pi}^{-}\), \(V_{po}^{+}\) and \(V_{po}^{-}\).

In the closed state, the electric field in the dielectric layer is on the order of 1 MV/cm. Because of this high field, charge is injected into the dielectric, which changes both the electric field present in the gap between the two plates and the amount of charge in the bottom and top electrode, thereby influencing the electrostatic force (Fig. 3). In case of a positive trapped charge, negative image charges will appear on the top and bottom electrode, which reduces the total amount of charge on the electrodes if a positive voltage is applied. The net effect of

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{Fig.1.png}
\caption{Schematic representation of an RF MEMS. The top electrode of a parallel plate capacitor can be pulled down by applying a voltage greater than the pull-in voltage \(|V| = |V_{pi}|\), which is pulled up again by the springs if the voltage is lowered beneath the pull-out voltage \(|V| = |V_{po}|\).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{Fig.2.png}
\caption{Typical \(CV\) curve of an RF MEMS capacitive switch. By increasing the voltage, the top electrode is pulled down and the capacitance increases. Above \(|V| = |V_{pi}|\) the switch closes. When the voltage is lowered again, the switch opens for \(|V| < |V_{po}|\).}
\end{figure}
the dielectric. This happens when failure of the switch due to stiction of the top electrode to charge. A large amount of injected charge can even lead to measurement setup. Two are based on determining measuring the shift of the instance, if \( V_{\text{pi}} \) in the closed branch of the hysteresis curve even at 0 V. For when \( V_{\text{pi}} \) becomes negative, the switch can be becomes positive or when \( V_{\text{po}} \) becomes negative. In that case the switch can be in the closed branch of the hysteresis curve even at 0 V. For instance, if \( V_{\text{po}} > 0 \), and the switch is closed by applying a voltage above \( V_{\text{po}}^{+} \), it will not open again when the voltage is suddenly set to zero.

In this paper we consider three different methods for measuring the shift of the \( CV \) curve with a low frequency measurement setup. Two are based on determining \( V_{\text{pi}} \) and one is based on determining the center shift of the \( CV \) curve, which to our knowledge has not been proposed before. The influence that the measurements have on the switches is investigated and is compared with results obtained with a fast RF-\( CV \) measurement setup. The new method, in contrast to other methods, does not degrade the switches and is used to characterize dielectric charging at several voltages.

II. MEASURING DIELECTRIC CHARGES

A. Setups and measurement methods

To study charge injection, \( V_{\text{shift}} \) is measured as a function of stress voltage and time. One of the setups with which these measurements can be done is depicted schematically in Fig. 5. To avoid moisture from influencing the measurements, the switches are stressed and measured in a dry nitrogen environment at atmospheric pressure. A bias voltage is provided by a Keithley 230 Programmable Voltage Source to a HP4275 LCR meter which is then used to measure the capacitance as function of voltage. The test signal of the LCR meter was 4 MHz. A picture of the switches which were used for the measurements is shown in Fig. 6.

The switches are stressed and \( V_{\text{shift}} \) is measured periodically. To measure \( V_{\text{shift}} \), three methods are considered:

1) Whole \( CV \) curve method: Measure the \( CV \) curve with equidistant steps from below \( V_{\text{pi}}^{-} \) to above \( V_{\text{pi}}^{+} \) back to below \( -V_{\text{pi}} \) again. Compare to the first \( CV \) curve by determining the pull-in and pull-out voltages [5], [6]. \( V_{\text{shift}} \) is determined by \( V_{\text{shift}} = V_{\text{pi}} - V_{\text{pi}}^{+} \).

2) Successive approximation method: Similar to the whole \( CV \) curve method, this method searches for the value of
the capacitance, measuring the LCR meter takes roughly 1 second to accurately measure for each measurement of $V_{shift}$. This way, $V_{shift}$ can even be measured when $V_{p0}^{\text{ls}}>0$ (or $V_{p0}^{\text{ls}}<0$), thereby extending the range of voltage shifts that can be measured.

To reduce the measurement time of $CV$ curves, a second setup with which we can do reliability measurements was constructed. Here, instead of an off-the-shelf LCR meter, a custom RF setup is used to measure the $CV$ curve. The bias voltage is provided by an amplified signal from a function generator. Compared to the LCR setup this RF setup has several advantages as well as disadvantages: while the capacitance can be measured very quickly, it is more difficult to implement, requires some tedious calibration steps and requires the capacitive switches to have a layout which is compatible with RF-probes. It also has a lower signal to noise ratio.

With the RF setup, capacitances are measured with a discrete single-frequency 1-port S-parameter measurement system based on the description given by Nieminen et al. [9] which is schematically depicted in Fig. 8. An RF signal (890 MHz) from a signal generator is split in two. One part goes into the local oscillator of the IQ-demodulator. The other part of the signal passes through a circulator, after which a bias voltage is added to the signal. The signal then reflects back from the RF MEMS capacitive switch. The reflected signal passes through the bias-T and the circulator to the RF-in port of the IQ-demodulator. The amplitude and phase of the reflected signal are determined from the I and Q signals using an oscilloscope. A 10-dB attenuator (Fig. 8) between the circulator and the signal port of the IQ-demodulator reduces the effect of small non-linearities in the IQ-demodulator. By first performing an open-short-load calibration, the capacitance can be calculated from the measured reflection. The capacitance measurement speed is high, and the $CV$ curve measurement time is limited by the mechanical response time of the MEMS: if the measurement is performed too quickly, the voltage changes while the switch is closing. In this case the flanks at pull-in and pull-out in the $CV$ curve are not vertical. To eliminate this effect, we measure a whole $CV$ curve in 400 ms, and parabolas for the center shift method in 100 ms. To increase the accuracy of the measurement, the average of two $CV$ curve is taken for the whole $CV$ curve method. The parabolas for the extraction of the center shift are measured and averaged 8 times. The successive approximation method is not used with the RF setup.

**B. Results: comparison of the measurement setups and methods**

In this section we compare the influence of the different measurement methods and setups on the measurement results. In Fig. 9 the effects and reproducibility of the determination of $V_{\text{shift}}$ with the different methods and setups are shown. No stress voltage was applied between consecutive measurements of $V_{\text{shift}}$. As can be seen, the measured values of $V_{\text{shift}}$ obtained with the center shift method only show a negligible

![Fig. 7. Center of the $CV$ curve before (black) and after (grey) a switch has been stressed at 65 volt for 727 seconds. By fitting a parabola through the data, the center $V_{\text{shift}}$ can be accurately determined.](image-url)
drift (less than 0.5 mV per measurement), while the measured values of $V_{\text{shift}}$ obtained with the whole $CV$ curve and successive approximation method show a significant change when measured repeatedly: with the successive approximation method the average drift of $V_{\text{shift}}$ is -12 mV/measurement, more than 40 times larger than the drift of the center shift method. The noise on the $V_{\text{shift}}$ is also low with the center shift method: the standard deviation with respect to the linear fit is 8.2 mV.

With the RF setup, there is no significant drift for both the center shift method and for the whole $CV$ curve method. This shows that if you measure the $CV$ curve fast enough, the whole $CV$ curve method can also be used. However, due to the lower signal-to-noise ratio of the discrete RF setup and the noise on the amplified voltage from the signal generator, there is a larger spread in the measured voltage shift. The standard deviation on the values of $V_{\text{shift}}$ determined with the RF center shift method is 0.17 V, which is mainly due to the uncertainty of the parabola fit. Although the accuracy of the parabola fit obtained with the RF setup is worse than the results obtained with the LCR setup (170 mV for the RF setup versus 8.2 mV for the LCR meter), the RF Setup faster (2.5 seconds versus 17 seconds). The standard deviation in the values of $V_{\text{shift}}$ determined from the change in $V_{\text{on}}$ is 0.08 V.

All in all, the results clearly show the necessity of measuring charging effects in the open state by using the center shift method, or to very rapidly measure the $CV$ curve to avoid that the measurement itself influences the result by using a fast RF setup. They further show that the LCR setup is slower and more accurate than the RF setup.

In Fig. 10 we have used the center shift method to determine the shifts in the $CV$ curve due to three different stress voltages. As one would expect, a higher stress voltage results in a faster and larger change of $V_{\text{shift}}$. According to Fig. 9, if these measurements had been done with the successive approximation method instead of the center shift method, a drift of about -0.47 V would have been induced during the 20 measurements of $V_{\text{shift}}$ which were conducted during the 30 minutes of applied stress. This would give a significant deviation: at 50 V the voltage shift of the $CV$ curve after 27 minutes was between 1.0 and 1.8. Even at 60 V, the drift part would have been 7.5% of the measured value. With the center shift method a drift of less than 6 mV is expected. This indicates that the use of the center shift method is much better suited to characterize charging, especially at lower stress voltages.

In Fig. 11 the RF setup is used to measure $V_{\text{shift}}$ (determined with the center shift method), and the positive and negative pull-in voltage extracted from the whole $CV$ curve as function of stress time at a stress voltage of 45V. Closer inspection reveals that the curves get closer together after more voltage stress has been applied. To make this clearer, the voltage axis in Fig. 11 has been divided in three parts. Additionally, the $V_{\text{shift}}$ has also been determined as $(V_{\text{on}}^+ + V_{\text{on}}^-)/2$. As can be seen, the results almost overlap with the results from the fitted parabola.

The phenomena of $CV$ curve narrowing has been observed before and an explanation for this has been proposed by Rottenberg et al. [10]: if the injected charge is laterally inhomogeneous, the internal $E$-field caused by the charge can never be completely compensated by applying a laterally homogeneous $E$-field. The net result is that there are two
effects: the center of the \( CV \) curve proportional undergoes a shift proportional to the mean of the injected charge, while the lateral inhomogeneity results in an extra contribution in the electrostatic force which is proportional to the standard deviation of the amount of injected charge. This causes the \( CV \) curve to narrow. Other causes for \( CV \) curve narrowing could be changes in the spring constant and the gap height.

From the observed \( CV \) curve narrowing we can conclude that even if the \( CV \) curve can be measured fast enough so that virtually no charge is injected during the \( CV \) measurement, \( V_{\text{shift}} \) should not be determined as a change in one of the pull-in voltages, but from the shift of the center of the \( CV \) curve. This center shift can be determined by fitting a parabola or from \( (V^+_{\text{pi}} + V^-_{\text{pi}})/2 \).

### III. Conclusions

The effects of charge injection in the dielectric layer of an RF MEMS capacitive switch are studied using a center shift measurement method which is both accurate (8.2 mV standard deviation on the LCR setup) and has less influence on the device under test than the commonly used procedure in noncontact capacitance-voltage measurements and simulations. The center shift method is both accurate and practical, as shown by the data. This allows homogeneous charging to be studied independently from \( CV \) curve narrowing effects. If experiments are done with RF equipment which quickly measure a \( CV \) curve, the effect of the measurement on the device becomes negligible. In this case \( V_{\text{shift}} \) may also be determined by \( (V^+_{\text{pi}} + V^-_{\text{pi}})/2 \).

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**References**


