Characterization of dielectric charging in RF MEMS

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Abstract—Capacitive RF MEMS switches show great promise for use in wireless communication devices such as mobile phones, but the successful application of these switches is hindered by the reliability of the devices: charge injection in the dielectric layer (SiN) can cause irreversible stiction of the moving part of the switch.

Our research comprises a study on charge injection by stressing the dielectric with electric fields on the order of 1 MV/cm, and by measuring the effects it has on the C-V curve.

Index Terms—RF MEMS, dielectric, charging, reliability.

I. INTRODUCTION

RF MEMS (Radio Frequent Micro-Electro-Mechanical Systems) capacitive switches show great potential for use in wireless communication devices such as mobile phones. This is due to the good RF characteristics and low power consumption of the switches [1]. Fig. 1 shows a schematic representation of an RF MEMS. The switch consists of two electrodes, of which the upper electrode is suspended by tiny springs. The top electrode of the device under study is 0.46 × 0.46 mm, the dielectric has a thickness of approximately 0.4 μm, and the air gap is approximately 5.2 μm. The upper electrode 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 and restoring spring force becomes unstable and the switch closes. This voltage is called the pull-in voltage $V_{\text{pi}}$. 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 beneath the so-called pull-out voltage $V_{\text{po}}$. $V_{\text{pi}}$ and $V_{\text{po}}$ can be found by measuring the hysteresis present in the capacitance-voltage curve of the switch. An example of such a C-V curve is given in Fig. 2.

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 in the dielectric, which changes the electric field present in the gap between the two plates. This superimposed E-field shifts the C-V curve [2], as will be shown in the next part. A large amount of injected charge can lead to failure of the switch due to stiction of the upper electrode to the dielectric.

II. QUANTITATIVE EFFECT OF CHARGE IN THE DIELECTRIC

If we assume that the switch behaves as a parallel plate capacitor the electrostatic force can be calculated by differentiating the total electrostatic energy in the capacitor ($U_E$) and in the voltage source ($U_V$) to the distance between the two plates. In our work, we focus on the charge injection due to E-field shifts the C-V curve [2], as will be shown in the next part. A large amount of injected charge can lead to failure of the switch due to stiction of the upper electrode to the dielectric.
plates:

\[ F_E = -\nabla(U_V + U_E) = \frac{d}{dh}QV - A \frac{d}{dh} \left( \int_0^d \frac{\varepsilon_0 k|E(z)|^2}{2} dz + \int_d^{d+h} \frac{\varepsilon_0 |E(z)|^2}{2} dz \right), \]

(1)

where \( A \) is the area of the plate, \( Q \) the charge provided by the voltage source to the capacitor, \( d \) the thickness of the dielectric, \( k\varepsilon_0 \) the permittivity of the dielectric, \( \varepsilon_0 \) the permittivity of air, \( h \) the distance of the plate to the top of the dielectric and \( E(z) \) the electric field at place \( z \) between the plate, with the bottom plate being \( z = 0 \). If no charges are present in the dielectric (Fig. 3a), the electric field has a value \( E_d \) in the dielectric and \( E_g \) in the airgap. By noting that \( kE_d = E_g \) and \( E_d \cdot d + E_g \cdot h = V \) \( E(z) \) can be calculated:

\[ E(z) = \begin{cases} \frac{V}{kh + d} & (0 < z < d) \\ \frac{V}{d} & (d < z < d + h) \end{cases} \]

Together with (1) and \( Q = CV = \varepsilon_0 AV/ (h + d/k) \) this leads to the electrostatic force in absence of electric charge:

\[ F = \frac{\varepsilon_0 AV^2}{2} \frac{d}{dh} \left( \frac{1}{h + \frac{d}{k}} \right) = -\frac{\varepsilon_0 AV^2}{2 \left( \frac{d}{k} + h \right)^2}. \]

(3)

If a fixed charge layer with density \( \sigma_d \) at \( z = z_\sigma \) is present, the surface charges at the top and bottom electrode are no longer equal and of opposite sign. The changes in the E-field (Fig. 3b depicts the case of \( z_\sigma = d \)) and the surface charge at the top electrode change the expression for the force [4]. It now becomes:

\[ F = -\frac{\sigma_d}{\varepsilon_0 k} \left( V - \frac{z_\sigma \sigma_d}{k\varepsilon_0} \right)^2. \]

(4)

The net effect of this change in the force is a horizontal shift \( V_{shift} \) in the C-V curve by

\[ V_{shift} = \frac{z_\sigma \sigma_d}{k\varepsilon_0}. \]

(5)

An example of this shift is given in Fig. 4. The shift of the C-V curve can lead to failure if the negative pull-out voltage shifts past the y-axis, in which case the closed switch will not open if the voltage is set to 0 V. Another problem is the fact that if \( V_{shift} > 0 \), a higher actuation voltage is required to close the switch.

### III. MEASURING DIELECTRIC CHARGES

#### A. Setup

To study the charge injection, \( V_{shift} \) is measured as a function of stress voltage and time. The setup with which these measurements are done is depicted schematically in 5. To avoid moisture from influencing the measurements, the devices are stressed and measured in a glovebox with a nitrogen environment at atmospheric pressure. A bias voltage is provided by a Keithley 230 Programmable Voltage Source to a HP4275 LCR meter which can then be used to measure the capacitance as function of voltage. A Labview program was written to automate the measurements. It stresses the device and periodically measures \( V_{shift} \). After each period of stress, the shift of the C-V curve relative to the unstressed state must be measured. Several methods were considered:

1) Measure the C-V curve from below \( -V_{pi} \) to above \( +V_{pi} \) back to below \( -V_{pi} \) again. Compare to the original C-V curve [5], [6].

2) Search for the value of \( V_{pi} \) with an algorithm which first measures the open and closed capacitance as a reference and then by successive approximation tries to find the voltage at which the capacitance is the closest to \((C_{open} + C_{closed})/2\). Note that after each guess for the pull-in voltage the switch must be allowed to open again.

3) Only measure the center part of the C-V curve and estimate the voltage at which the capacitance has the lowest value.

Method 1 has the disadvantage that for each measurement of \( V_{shift} \), the capacitance has to be measured a lot of times. Since the LCR meter takes roughly 1 second to accurately measure the capacitance, measuring \( V_{shift} \) takes a significant amount of time so that during the measurement of \( V_{shift} \) charge can leak.
away again. Also, voltages above $V_{51}$ have to be applied so that
the switch 'sees' additional stress during the determination of $V_{\text{shift}}$. Method 2 is faster and also more accurate, but still has
one of the problems of method 1: during the measurements voltages above $V_{51}$ have to be applied. This leaves method 3,
which is both fast and has no risk of charging the dielectric
further during the determination of $V_{\text{shift}}$. Since a large $V_{\text{shift}}$
can prevent the switch from opening at 0 V after a period of
stress, the voltage is actually first set to the previous measured
value of $V_{\text{shift}}$, rather than 0 V, before attempting to measure
the new value of $V_{\text{shift}}$.

B. Results

In Fig. 6 the resulting shifts in the C-V curve due to
three different stressing voltages are shown. As one would
expect, a higher stress voltage results in a faster and larger change of $V_{\text{shift}}$. It is also clear from the measurements that at
higher stress voltage the spread in the measured voltage shifts
becomes larger. It is speculated that this spread in the charging
is due to variations in the thickness $d$ of the dielectric and
surface roughness of the upper electrode, which leads to a rest
air gap $h_{\text{closed}}$ between the upper electrode and the dielectric
in the closed state. Since the electric field is proportional to
the applied voltage and inversely proportional $\frac{d}{k} + h_{\text{closed}}$ (2),
variations in the nitride thickness and surface roughness lead to
variations in the electric field:

$$\sigma_E = \left( \frac{V}{\frac{d}{k} + h_{\text{closed}}} \right)^2 \sigma_{\frac{d}{k} + h_{\text{closed}}}.$$ (6)

The variations in $E$ are thus proportional to variations in $\frac{d}{k} + h_{\text{closed}}$ and to variations in $E$ itself. This in turn leads to the
larger spread in the charging curves at 70 V.

Another interesting thing to note is that at least two competing mechanisms, with different time-scales, are found (Fig.
7) after prolonged stressing of the dielectric. Here $V_{\text{shift}}$ first
increases, indicating the injection of a positive charge by
the positive top electrode, followed by a decrease of $V_{\text{shift}}$, indicating a compensation of the positive charge by negative
charges injected by the lower electrode.

IV. CONCLUSIONS AND OUTLOOK

In this paper initial results of a study on dielectric charging
in RF MEMS are shown. The shift of the center of the C-V
curve of such a capacitive switch is used as a measure for
the injected charge. At higher voltages the devices not only show quicker and larger shifting of the C-V curve, but also
a larger spread in the measured shifting curves, which can
be attributed due to variations in the dielectric thickness and
surface roughness.

For long durations of applied stress the shift of the C-V
curve rises and decreases again, indicating two different charge
injection mechanisms working at different timescales.

We intend to study dielectric charging of RF MEMS further
by measuring with a different setup which can accurately
control the temperature. The temperature and stress voltage
dependent measurements will lead to a greater understanding
of an important failure mechanism of RF MEMS.

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Fig. 5. Schematic view of the measurement setup. A Labview computer
program controls a HP4275 LCR meter and an Keithley 230 voltage Pro-
grammable Voltage Source. The LCR meter is connected to the RF MEMS
devices, which are stressed and measured in a dry $N_2$ atmosphere.

Fig. 6. Shift of C-V curve as function of time at room temperature for 50,
60 and 70 V stress. Spread in the measured results is higher at higher stress
voltages.

Fig. 7. Shift of C-V curve as function of time at room temperature for 60
V. At first positive charges increase $V_{\text{shift}}$, which is later on compensated by
negative charges.
References


