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 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 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 top electrode is suspended by tiny springs. The top 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_{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_{po}). V_{pi} and V_{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 top 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:

$$F_E = -\nabla(U_V + U_E) = \frac{\mathrm{d}}{\mathrm{d}h}QV - A\frac{\mathrm{d}}{\mathrm{d}h}\left(\int_0^d \frac{\epsilon_0 k|E(z)|^2}{2}\mathrm{d}z + \int_d^{d+h} \frac{\epsilon_0 |E(z)|^2}{2}\mathrm{d}z\right), \qquad (1)$$

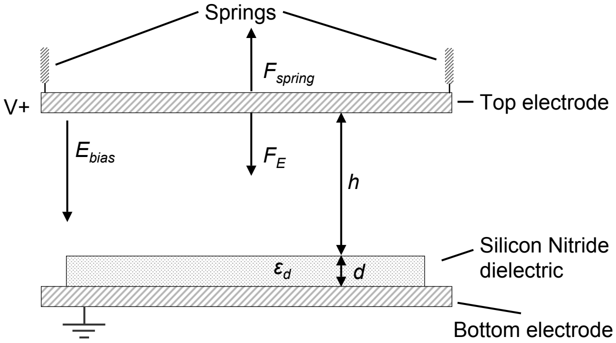

Fig. 1. Schematic representation of an RF MEMS. The top electrode of a parallel plate capacitor can be pulled down by applying a voltage greater than the pull-in voltage ($V > V_{\mathrm{pi}}$), which is pulled up again by the springs if the voltage is lowered beneath the pull-out voltage ($V < V_{\mathrm{po}}$). The top electrode of the device under study is $0.46 \times 0.46\ \mathrm{mm}^2$, the dielectric has a thickness of approximately $0.4\ \mu\mathrm{m}$, and the air gap is approximately $5.2\ \mu\mathrm{m}$.

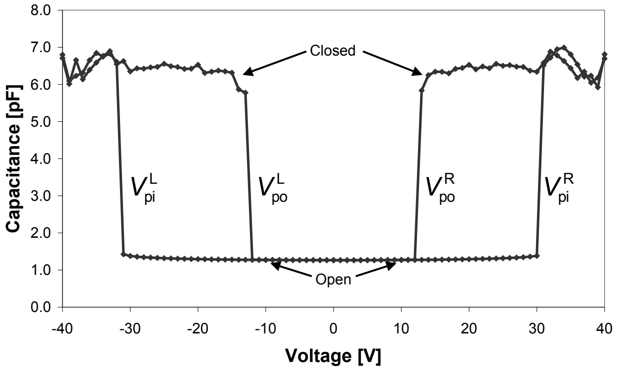

Fig. 2. Typical C-V curve of an RF MEMS. By ramping the voltage up, the top electrode is pulled down and the capacitance increases. Above $V = V_{\mathrm{pi}}$ the switch closes. When the voltage is ramped down again, the switch opens for $V < V_{\mathrm{po}}$.

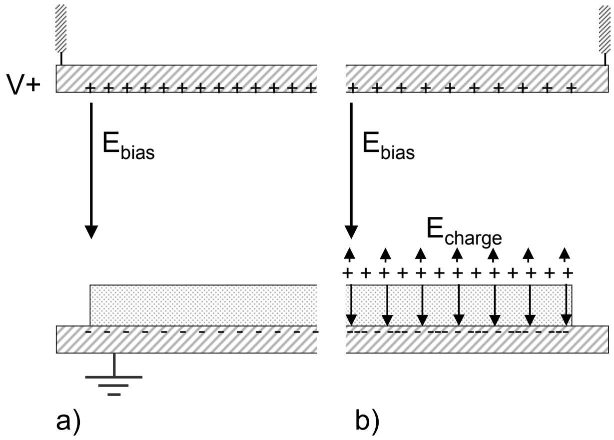

Fig. 3. E-field in a parallel plate capacitor. a) No fixed charges in the dielectric. b) Fixed surface charge at height $z = d$.

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, $k\epsilon_0$ the permittivity of the dielectric, ϵ_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:

$$E(z) = \left\{ \begin{array}{cc} \frac{V}{kh+d} & (0 < z < d) \\ \frac{V}{h+\frac{d}{k}} & (d < z < d + h). \end{array} \right\} \tag{2}$$

Together with (1) and $Q = CV = \epsilon_0 AV/\left(h + d/k\right)$ this leads to the electrostatic force in absence of electric charge:

$$F = \frac{\epsilon_0 AV^2}{2} \frac{\mathrm{d}}{\mathrm{d}h} \left(\frac{1}{\frac{d}{k} + h} \right) = -\frac{\epsilon_0 AV^2}{2\left(\frac{d}{k} + h\right)^2}. \tag{3}$$

If a fixed charge layer with density σ_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:

$$F = -\frac{\epsilon_0 A \left(V - \frac{z_\sigma \sigma_d}{k\epsilon_0}\right)^2}{2\left(\frac{d}{k} + h\right)^2}. \tag{4}$$

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

$$\boxed{V_{\mathrm{shift}} = \frac{z_\sigma \sigma_d}{k\epsilon_0}.} \tag{5}$$

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 $V_{\mathrm{shift}} > 0$, a higher actuation voltage is required to close the switch.

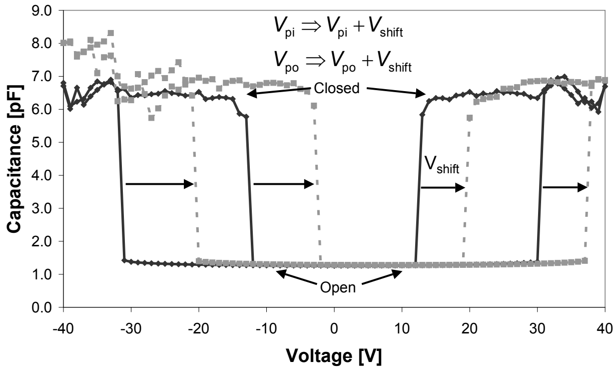

Fig. 4. C-V curve before (black) and after (grey) a device has been stressed at 65 volt for 727 seconds.

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 Fig. 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 with equidistant steps from below $V_{\mathrm{pi}}^{\mathrm{L}}$ to above $V_{\mathrm{pi}}^{\mathrm{R}}$ back to below $V_{\mathrm{pi}}^{\mathrm{L}}$ again. Compare to the original C-V curve by determining the pull-in and pull-out voltages [5], [6]. V_{shift} is determined by $V_{\mathrm{shift}} = V_{\mathrm{pi}} - V_{\mathrm{pi}}^{t=0}$.
2) Similar to method 1, this method searches for the value of V_{pi} by an algorithm based on successive approximation. Note that after each guess for the pull-in voltage the switch must be allowed to open again. Again, V_{shift} is determined by $V_{\mathrm{shift}} = V_{\mathrm{pi}} - V_{\mathrm{pi}}^{t=0}$.
3) Only measure the shift of the center (opened switch) part of the C-V curve by estimating the voltage at which the capacitance has the lowest value. This is done by fitting a parabola $C(V) = a \cdot (V - V_{\mathrm{shift}})^2 + C_{\mathrm{open}}$ through the center of the C-V curve (Fig. 6). Since the electrostatic force is proportional $(V - V_{\mathrm{shift}})^2$ [4], $C(V)$ is symmetric around $V = V_{\mathrm{shift}}$, therefore this fitted parabola accurately determines V_{shift}. To our knowledge, this is a new method, since another non-contact method [7] requires RF measurements.

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

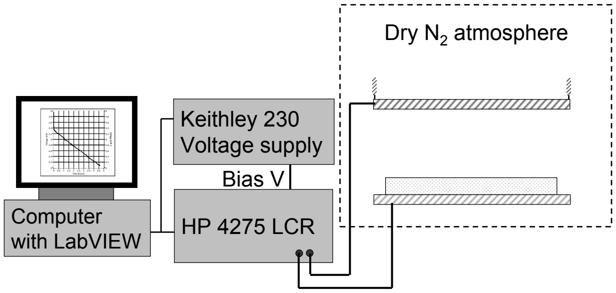

Fig. 5. Schematic view of the measurement setup. A LabVIEW computer program controls a HP4275 LCR meter and an Keithley 230 voltage Programmable Voltage Source. The LCR meter is connected to the RF MEMS devices, which are stressed and measured in a dry N_2 atmosphere.

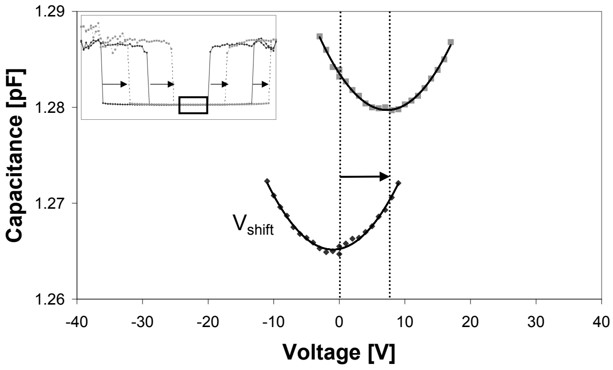

Fig. 6. Center of the C-V curve before (black) and after (grey) a device has been stressed at 65 volt for 727 seconds. By fitting a parabola through the data, the center V_{shift} can be accurately determined.

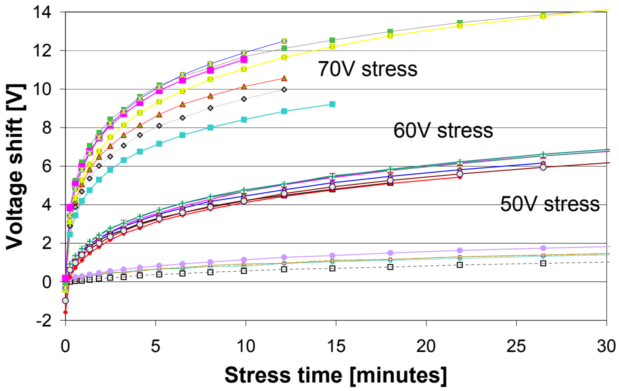

Fig. 7. Shift of C-V curve as function of time at room temperature for 50, 60 and 70 V stress. Spread in the measured results is higher at higher stress voltages.

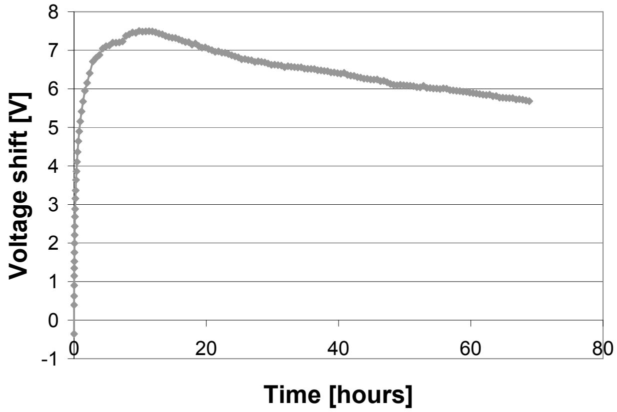

Fig. 8. Shift of C-V curve as function of time at room temperature for 60 V stress. At first positive charges increase V_{shift}, which is later on compensated by negative charges.

time so that during the measurement of V_{shift} charge can leak away again. Also, voltages above V_{pi} have to be applied so that the switch 'sees' additional stress during the determination of V_{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_{pi} 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_{shift}. Since a large V_{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_{shift}, rather than 0 V, before attempting to measure the new value of V_{shift}.

B. Results

In Fig. 7 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_{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 top electrode, which leads to a rest air gap h_{closed} between the top electrode and the dielectric in the closed state. Since the electric field is proportional to the applied voltage and inversely proportional to $\frac{d}{k}+h_{\text{closed}}$ (2), variations in the nitride thickness and surface roughness lead to variations σ_E in the electric field:

$$\begin{aligned}\sigma_E &= \left|\frac{\mathrm{d}}{\mathrm{d}(\frac{d}{k}+h_{\text{closed}})}E\right|\sigma_{\frac{d}{k}+h_{\text{closed}}}\\ &= \left|\frac{V}{\left(\frac{d}{k}+h_{\text{closed}}\right)^2}\right|\sigma_{\frac{d}{k}+h_{\text{closed}}}.\end{aligned} \tag{6}$$

The variations in E are thus proportional to variations in $\frac{d}{k}+h_{\text{closed}}$ and to E itself. Since the charging speed rapidly increases with E, the variations in E translate to a 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. 8) after prolonged stressing of the dielectric. Here V_{shift} first increases, indicating the injection of a positive charge by the positive top electrode, followed by a decrease of V_{shift}, indicating a compensation of the positive charge by negative charges injected by the bottom 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.

After the initial rise of V_{shift}, for long durations of applied stress the shift of the C-V curve decreases again, indicating two different charge injection mechanisms working at different timescales.

We intend to study dielectic 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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