Time and voltage dependence of dielectric charging in RF MEMS capacitive switches

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Abstract—A major issue in the reliability of RF MEMS capacitive switches is charge injection in the dielectric. In this study we try to establish the time and voltage dependence of dielectric charging in RF MEMS with silicon nitride as a dielectric. It is shown that the voltage shift of the CV-curve due to injected charge shows a $\sqrt{t}$ dependence over a large time range. By doing measurements on a large number of devices (early development material made at NXP Semiconductors in Nijmegen) we further show that the charging rate increases exponentially with the applied stress voltage.

Index Terms—RF MEMS, capacitive switch, dielectric, charging, reliability, silicon nitride.

I. INTRODUCTION

RF MEMS (Radio Frequency Micro-Electro-Mechanical Systems) capacitive switches show great potential for use in wireless applications. Desirable aspects are the good RF characteristics (such as high linearity and low losses) and the low power consumption [1]. However, obtaining a high reliability is a major challenge for the successful implementation of the switches in commercial products.

The most important mechanism that causes degradation of the switch is the injection and trapping of charge into the dielectric layer due to the applied electric field [1]–[7]. The injected (and subsequently trapped) charge redistributes the internal E-field and results in a built-in voltage that shifts the CV-curve of the device [6]–[8]. This shift may even be large enough to cause the pull-out voltage to shift past $V = 0$, after which the device will not open when the bias voltage is removed.

Experiments have shown [2], [9], [10] that the shift in the CV-curve increases with time and stress voltage, but the exact mechanism and time behavior are not known. Although several models for the time and stress voltage dependence of the voltage shift have been proposed, the experimental verification of these models was usually done on a limited number of samples and/or over a small voltage and time range. In this study we present new measurement data obtained on early development material made at NXP Semiconductors in Nijmegen with a fast capacitance measurement setup, which allows accurate measurements of changes in the CV-curve over a wide time and voltage range. From these data we conclude that the time and voltage dependence of the shift in the CV-curve are described by $V_{\text{shift}} = \alpha \sqrt{t} \exp (\beta V_{\text{stress}})$.

II. SWITCHING BEHAVIOR AND EFFECT OF CHARGE INJECTION

A schematic representation of an RF MEMS capacitive switch is shown in Fig. 1. The switch consists of two electrodes, a dielectric layer (silicon nitride, 425 nm thick) and an air gap. The top electrode is suspended by springs. In our case the electrode material is an AlCu alloy, and the dielectric is a silicon nitride with a thickness of 425 nm.

When a voltage is applied across the two electrodes, the electrostatic force $F_E$ will pull the electrode downward until it is in equilibrium with the restoring mechanical spring force $F_{\text{spring}}$. Above a certain voltage, called the pull-in voltage $V_{\text{pi}}$, the balance between $F_E$ and $F_{\text{spring}}$ becomes unstable and the switch closes, which is marked by a sudden increase in the capacitance. Since the distance between the two electrodes is relatively small in this position, the electrostatic force is larger than the restoring force in the closed state, so that when the voltage is decreased again, the switch will not open at $V = V_{\text{pi}}$ but at a lower voltage, the pull-out voltage $V_{\text{po}}$. As the electrostatic force is proportional to the voltage squared, this pull-in and pull-out behavior is present for both positive and negative voltages.

When the switch is in the closed position, an electric field of the order of typically 1 MV/cm is present. Due to this field charge is injected and trapped in the dielectric, causing a change in the electric field. The net effect of the trapped
Fig. 2. CV-curve before (black) and after (grey) it has been stressed at 60 V for 300 seconds. a) The voltage of minimal capacitance shifts to the right due to trapped holes. b) Narrowing of the CV-curve. c) Combined effect of both shifting and narrowing of the CV-curve is visible.

charges is thus a built-in voltage $V_{\text{shift}}$ which shifts the CV-curve [5]–[8]. In Fig. 2a this can be observed as a change in the voltage at which the CV-curve is minimal. $V_{\text{shift}}$ is proportional to the amount of injected charge: positive charge will shift the CV-curve to the right, negative charge shifts it to the left. The position of the injected charge is also important: injected charge located close to the surface of the dielectric is more important than charge located near the bottom electrode, because the effect of charge near the bottom electrode is less due to mirror charges in the electrode [5].

Another effect that can take place is a narrowing of the CV-curve (see Fig. 2b) [9]. An explanation [11] for the narrowing effect is that charge may not be homogeneous in the lateral direction. If this is the case, the inhomogeneous field can not be completely cancelled by the homogeneous applied field caused by the bias voltage. The result is that there is always an electrostatic force, so that the pull-in and pull-out voltages nire closer together. An example of the combined effect of shifting and narrowing is shown in Fig. 2c.

Both shifting and narrowing of the CV-curve cause reliability problems when one of the pull-out voltages shifts past $V = 0$: a closed switch will not open again when the bias voltage is set to zero.

III. MEASUREMENT METHOD AND SETUP

The experiments consist of a constant-voltage stress, interrupted at increasing time intervals for a low-voltage measurement of the CV-curve shift. We determine $V_{\text{shift}}$ by fitting a parabola $C(V) = c \cdot (V - V_{\text{off}})^2 + C_{\min}$ through the central part of the CV-curve. $V_{\text{off}}$ is then the voltage at which the capacitance has the lowest value (Fig. 2a). At $V = V_{\text{off}}$, the applied electric field cancels the electric field in the gap caused by the trapped charges, resulting in the smallest capacitance value. We then define the voltage shift $V_{\text{shift}}(t)$ as $V_{\text{off}}(t) - V_{\text{off}}(t = 0)$. In a previous study [12], we showed that this low-voltage measurement method causes less device degradation than conventional CV tests. An additional advantage is that CV-curve narrowing will not affect the determination of $V_{\text{shift}}$, which makes it possible to study shifting and narrowing separately. The measurements are conducted on unpackaged devices, with a dry $N_2$ flow to prevent adverse effects due to moisture.

Capacitances are measured with an 1-port RF measurement system based on the description given by Nieminen et al. [13] which is schematically depicted in Fig. 3. It works as follows: an RF signal from a signal generator is split in two. One part goes into the local oscillator of the IQ-demodulator. To the other part a DC bias is added. The signal passes through a circulator and reflects back from the RF MEMS capacitive switch. The reflected signal passes through the circulator and a 100 pF decoupling capacitor 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. 3) minimizes the effect of small nonlinearities in the IQ-demodulator. To the other part a DC bias is added. The signal passes through a circulator and reflects back from the RF MEMS capacitive switch. The reflected signal passes through the circulator and a 100 pF decoupling capacitor 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. 3) minimizes the effect of small nonlinearities in the IQ-demodulator. By first doing an open-short-load calibration, the capacitance can be calculated from the measured reflection. The capacitance measurement speed is very fast, and the CV-curve measurement time is limited by the
the capacitance can be determined. Of the reflected RF signal are measured with an IQ-demodulator, from which

Fig. 3. Schematic of the 1-port RF measurement system. Phase and amplitude of the reflected RF signal are measured with an IQ-demodulator, from which the capacitance can be determined.

mechanical response time of the MEMS: if the measurement is performed too quickly, the flanks at pull-in and pull-out in the CV-curve are not vertical. To rule out this effect, we measure a CV-curve in 400 ms.

IV. MEASUREMENTS AND INTERPRETATION

In Fig. 4a an example of the measured $V_{\text{shift}}$ as function of stress time is given. On a double-logarithmic scale (Fig. 4b), the points are approximately on a straight line with a slope around 0.56.

It is therefore tempting to follow previous works in using a few-parameter model to describe the behavior of $V_{\text{shift}}(t)$ at a fixed stress voltage. Spengen et al. [5], Yuan et al. [10], and Papaioannou et al. [14] describe charge build-up in the dielectric with an exponential time dependence indicating a fixed amount of traps which are slowly filled by the leakage current.

Since in the closed state the capacitive switch is similar to a MIM capacitor, reliability literature on these devices may also offer relevant models. Lau et al. [15], Shannon et al. [16], van Delden et al. [17], and Street [18] link degradation of amorphous silicon and silicon nitride to the generation of metastable defects by currents, with mechanisms related to light-induced changes in amorphous silicon [19], [20]. They find that the defect density is proportional to the square root of $t$. Redfield et al. [21] interpret generation of metastable defects in another way and propose a stretched-exponential time dependence.

Hence, we compare the three following time evolutions of $V_{\text{shift}}$:

$$V_{\text{shift}}(t) = V_{\text{max}} \cdot (1 - \exp(-kt)) + V_0$$

(1)

$$V_{\text{shift}}(t) = a\sqrt{t} + V_0$$

(2)

$$V_{\text{shift}}(t) = V_{\text{max}} \cdot (1 - \exp(-kt^\delta)) + V_0.$$  

(3)

In these equations $V_{\text{max}}$, $k$, $a$ and $\delta$ may all depend on the stress voltage and temperature. The extra fit parameter $V_0$ was added to each model to account for small systematic errors in the determination of $V_{\text{shift}}$ - induced e.g. by the limited accuracy of the $V_{\text{off}}(0)$ measurement value.

The data in Fig. 4b lie approximately on a straight line with slope 0.56, which hints in the direction of the square root behavior also found in the degradation of MIM capacitors. If we fit the function $V_{\text{shift}}(t) = a\sqrt{t} + V_0$ to the data we get a good agreement between the measurement data and the fitting result (see Table I). The accuracy of each $V_{\text{shift}}$ data point from the parabolic fit procedure amounts to 30 mV. Additional unquantified fluctuations include temperature variations (on very long time scales correlation between charging speed and temperature changes due to day/night cycles were observed) and relaxation of the injected charge during the determination of $V_{\text{shift}}$ (on short time scales the time it takes to determine $V_{\text{shift}}$ becomes comparable to the stress time between two data points). The fit with model 1 suggests that the overall error per measurement is 50 mV. The fitted value of $V_0$ is 39 ± 15 mV, which is small enough to be compatible with the notion that it is only added to account for the small systematic error made due to the limited accuracy of $V_{\text{off}}(0)$.

In table I, the fit results of the other two models are also presented. The $\chi^2$/D.O.F. is a measure of the distance of the points to the curve (normalized to the measurement error) and a lower value objectively indicates a better fit, even if the measurement error is not known exactly. Clearly, the exponential fit (model 1) gives a poor description of the data, while the other two models are satisfactory. However, the stretched-exponential equation fit does not converge to a final result: while $\delta$ converges to 0.53 ± 0.03, $V_{\text{max}}$ and $k$ turn out to be highly correlated, with $k$ very small and $V_{\text{max}}$ very large.

Fig. 4. Measured $V_{\text{shift}}$ as function of stress time. $V_{\text{stress}}$: 40 V. a) Linear axes. b) Double Logarithm axes with three different fit function.
find that the time and voltage behavior of dielectric charging state that the lifetime decreases exponentially with \( V \) with \( V \) the range of stress voltages the slope increases exponentially from device to device, from this graph it is clear that within of stress voltage in Fig. 6. Although there is quite some spread root time dependence was obtained. It is plotted as a function in RF MEMS capacitive switches can be described with the straightforward equation:

\[ V_{\text{shift}}(t) = \alpha \sqrt{t} \exp(\beta V_{\text{stress}}), \]

for which in our case \( \alpha \approx 2.4 \times 10^{-4} \text{ V/s}^{1/2} \) and \( \beta \approx 0.12 \text{ V}^{-1} \).

### V. CONCLUSIONS

A thorough investigation of the charge injection in RF MEMS capacitive switches is presented. We collected a large amount of measurement data using a refined stress-measure sequence. The dielectric charging, expressed as the voltage shift of the minimum capacitance value, shows a dependence with the square-root of time and the exponent of stress voltage over a wide range of stress conditions. This is a strong indicator that dielectric charging is governed by charge trapping in current induced metastable defects, which is also responsible for changes in the conductivity of silicon nitride MIM capacitors.

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### REFERENCES


