Charge Trap Investigation Methodology on RF-MEMS Switches

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Abstract. We hereby discuss effects and consequences of using certain measurements approaches on the charge trap analysis of RF-MEMS switches during cycling tests. We analyze how measurements are affected when the shape of the pulse changes, when the cycling frequency decrease and when measurements are carried out as a function of temperature. The trends here presented must to be taken into account when devices, that suffer of severe charge trapping phenomena, like those used in the following experiments, are considered. The real goal in fact, is to fully characterize the real performances of the devices separating the effects that different measurements analysis have on the device itself.

1. Introduction

RF-MEMS switches combine excellence electrical responses such as high isolation, ultra low-losses and high liner response with the well known advantages provided by the solid state fabrication processes, like reduced size, power consumption and costs of high volume products.

These devices are nowadays among the most promising technologies for terrestrial and satellite telecommunication systems because of their advantages, even though some issues, especially related with reliability and packaging [1], have not been resolved yet.

As regards reliability aspects both mechanical and electrical issues as well as semiconductor phenomena are often present leading, sometimes, to unreliable devices especially for high requirements applications like those related with space and aerospace market. In particular contact degradation [2], charge trapping phenomena [3], elastic/plastic deformations, fractures and structural elements stresses can be named. For the scope of our work, it has to be underlined that charge trapping issues appeared to be the dominant effect on devices. Charge trapping, i.e. the physical effect that traps charge carriers usually into the oxide layers, heavily modifies both electrical and mechanical properties of devices until charges are in somehow released. This usually causes an apparent early grave of devices. The necessity of fully characterize RF-MEMS on all their aspects requires several analysis approaches such as measurements at different frequencies, analysis carried out as a function of temperature as well as cycling tests [4] with different pulse shapes. Charge trapping phenomena though, combined with the effects induced by these methods, might lead to unclear or even counterintuitive results since different aspects combine together in a common outcome.

The aim of this work is to explain the role of each measurements aspects involved and, therefore, to separate charge trapping effects from those caused by different measurements approaches. In such a way we aim to a better understand the actual performances of devices measured, which is always the ultimate goal.

In particular, the effect of different pulse shapes, different plate temperature and, eventually, the effect of different frequencies are considered. For each of these aspects we provide experimental results and their interpretation.

When measuring devices that considerably suffer of charge trapping issues, the reader should take into account results proposed in this work in order to better understand how the effect of these analysis methods overlaps with trapped charges.

2. Technology Process and Measurement Setup

The devices have been fabricated at FBK by employing a well established process for RF-MEMS switches based on surface micromachining techniques combined to standard CMOS technology processing steps. The schematic flow of the 8 mask process is shown in Figure 1.

Initially on the p-type 5 kΩ silicon substrates a 1000 nm thick thermal oxide is grown. Next a 630 nm thick polysilicon layer is deposited, slightly doped by ion implantation and defined by photolithography and etching. In the next step a multi layer metallization of Ti/TiN/Al/Ti/Ti is deposited by sputtering for a total thickness of 630 nm in order to equal the thickness of the polysilicon layer. In turns, this metal layer is protected with 100 nm of a low temperature oxide obtained by

Low Pressure Chemical Vapor Deposition (LPCVD) from silane. At this point a 3 μm thick photoresist layer is deposited. After the evaporation of a 25 nm thick gold layer (with an 3 nm thick chromium film as adhesion layer underneath) in a first galvanic process a 1.8 μm thick gold layer is deposited in areas defined by photoresist. With a second galvanic process an approximately 4 μm thick gold layer is deposited, again defined by photoresist.

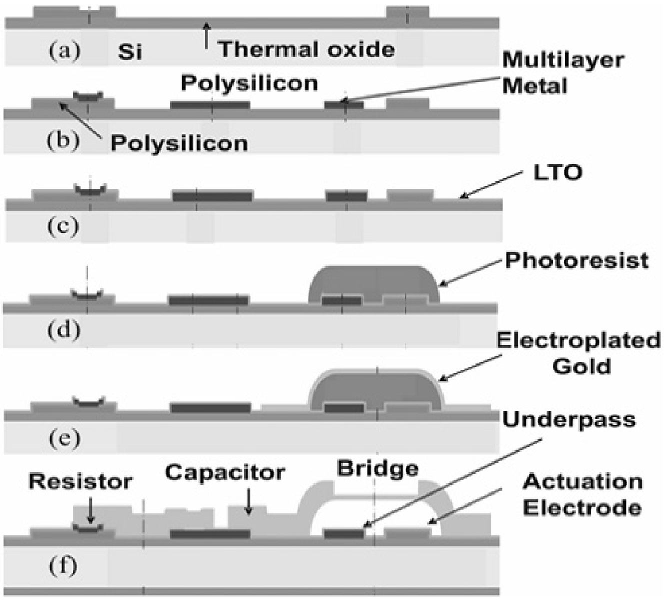

Fig. 1. Micromachining techniques description: 8 mask process from silicon substrate to gold membrane.

Ohmic series switches have been fabricated and in Figure 2 we report S_{21} versus bias voltage taken from a typical device that clearly shows low losses and high isolation. It must be stressed that all the measurements carried out in this work, have been carried out on wafer level in air, at controlled temperature, but not in nitrogen atmosphere. This is clearly the reason for the relatively low lifetime obtained in these test (as it will be shown later). The aim of this work, however, was to study the charge trapping mechanisms, in the devices and not the lifetime evaluation.

The actuation voltage is about 20 V while the release voltage is close to 16 V. The DC bias voltage used in cycling tests has been chosen at 40 V in order to obtain a good actuation of the device. The setup used in our experiments consists of a vector network analyzer used to monitor S-parameters, a waveform generator and a pulse generator used to generate the actuation waveform during cycling and a source meter used during DC characterization.

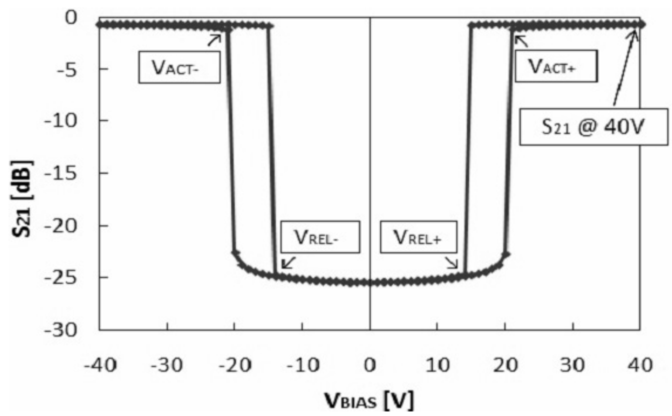

Fig. 2. S_{21} parameter vs. bias voltage for a typical device.

3. Analysis Methods and Their Effects

A. The effect of the pulse shape

Three different cycling pulse shapes, shown in the inset of Figure 4, have been used and compared in terms of their effect on the measurements. It is hereby shown that, by using different shapes for the cycling pulse, more or less charge is trapped [5].

First of all, we notice that degradation of scattering parameters can be mainly attributed to the charge trapping phenomena, since no significant permanent degradation has been measured once trapped charges was released.

To highlight the charge trapping phenomena in these devices (leading to a recoverable degradation), a cycling test has been carried out by setting the DC bias voltage below the actuation voltage, see Figure 3.

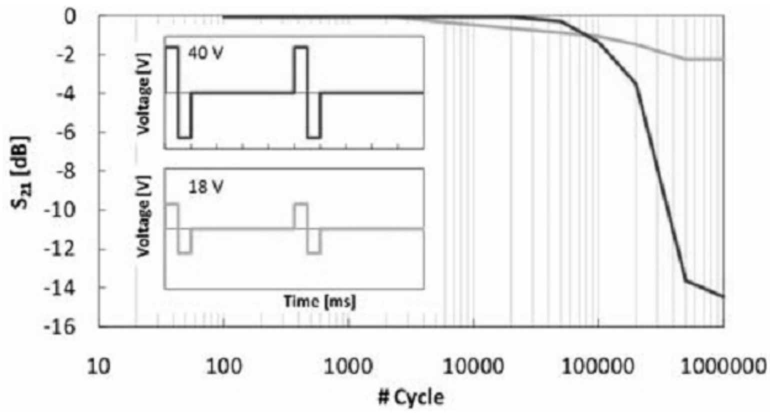

Fig. 3. S_{21} parameter vs. number of cycles with a bias voltage set above and below the actual device actuation voltage.

In such a way, in fact, the bias voltage was slightly less than the one required to lift the bridge down, but strong enough to create a significant electric field and hence charge trapping, in the MEMS structure. As see in Figure 3 a slight (but relevant) S21 degradation is observed, also when cycling the MEMS below the actuation voltage (orange curve, with VSTRESS = 18V). Since no mechanical contact degradation can happen in this experiment, this is an indirect confirmation that charge trapping is present in these devices.

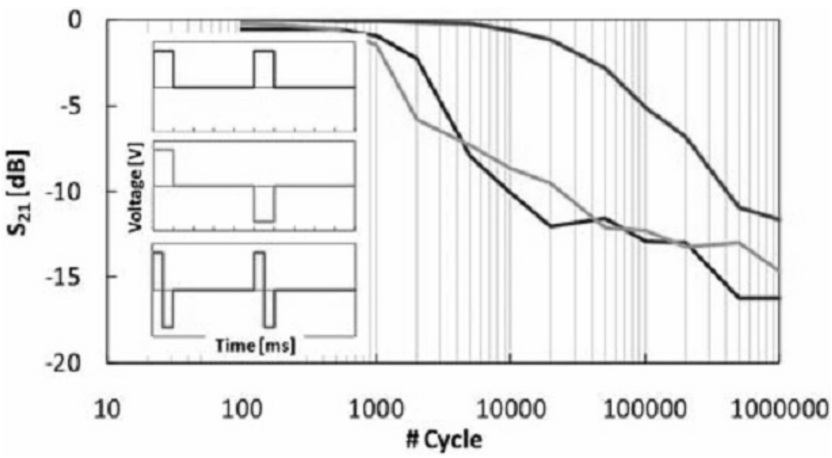

Fig. 4. Average S_{21} parameter vs. number of cycles of the same device cycled with different pulse shapes. The S_{21} parameter values are taken at 40 V.

Once we proved that charge trapping issues affects these devices during cycling tests, we investigated how different pulse shapes affect the behavior. Figure 4, shown the degradation of the S_{21} parameter during cycling in three representative series ohmic switches, driven with different pulses. The RF-MEMS switches, cycled with unipolar and alternating bipolar pulses (blue and green curves), show large S_{21} degradation after only 103 cycles. The dual-polarity pulse shape within the same period (the red curve in Figure 4), shows an improvement of the sustainable cycles (up to about 0.1 Million Cycles).

This is a clear indication that these dual polarity pulses (within the same period) largely mitigate charge trapping effects with respect to the other pulses. Another possible reason for the larger lifetime, induced by these bipolar pulses, could be related to a certain attenuation of the strength with which the contacts collapse one on the others, leading to a lower mechanical degradation.

The different effect caused by the double pulse within the same period and the one in which positive and negative bias alternates to each other, is still under investigation. However we have to point out that the inversion of polarity in the former pulse is fast enough so that the cantilever membrane does not have time to detach while the electric field inversion mitigate the trapped charge. At least three devices, with identical design and taken from different wafer area have been cycled and averaged for each pulse shape. In conclusion we have just shown that, by using different pulse shape, we can mitigate charge trapping on the device and by knowing these effects we can largely improve the lifetime of these RF-MEMS switches.

B. Effect of the temperature

Having proved that these devices suffer from severe charge trapping issues, during cycling tests, we wanted to investigate the effect of temperature. By the means of a thermal chuck we have tested "on-wafer" devices at different temperatures (from ambient to +70°C). The energy provided in such a way was expected to be partially transferred to charges in those midway energy levels that trap electrons, allowing in such a way their releasing. Surprisingly, we have actually measured a worsening of the scattering parameters, when testing the RF-MEMS at higher temperature, as shown in Figure 5.

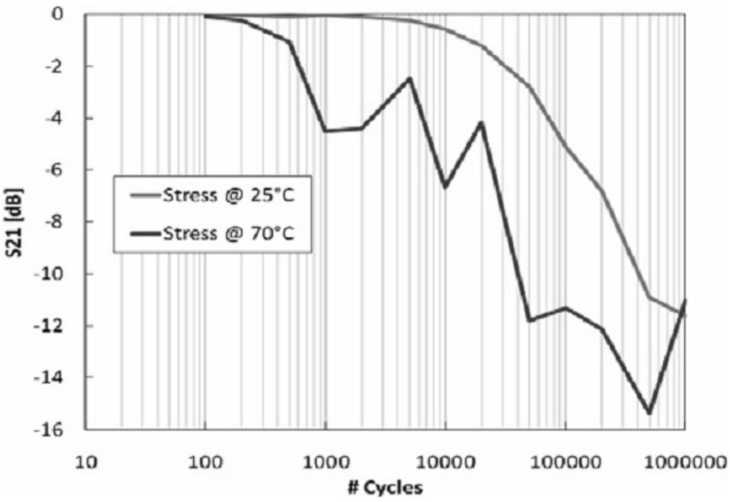

Fig. 5. Average S_{21} parameter vs. number of cycles of the same device cycled at different temperatures. The higher the temperature, the faster a switch is damaged. The S_{11} parameter, shows the same behavior.

This result can be explained as follow. Since the pulse shape used in our tests was the dual polarity one within the same period (third in Figure 3), trapped charges effects was already largely reduced thanks to the adopted dual polarity pulse shaping. Also we observed that the degradation observed in the RF-MEMS using the dual polarity pulse, is non-recoverable. This suggests us that the degradation in this case is related to the mechanical deformation of the switch. As a consequence, by increasing the temperature, device became more prone to plastic deformation and this can explain the lower lifetime of the switches at high temperatures [6].

C. Effect of frequency

We also confirmed that the choice of the cycling frequency (using unipolar pulses) can affect the charge trapping phenomena. As shown in Figure 6, in fact, a lower cycling frequency seems to reduce the lifetime of a device in terms of number of cycles by trapping more charges, compared to the one of an identical device that switches faster.

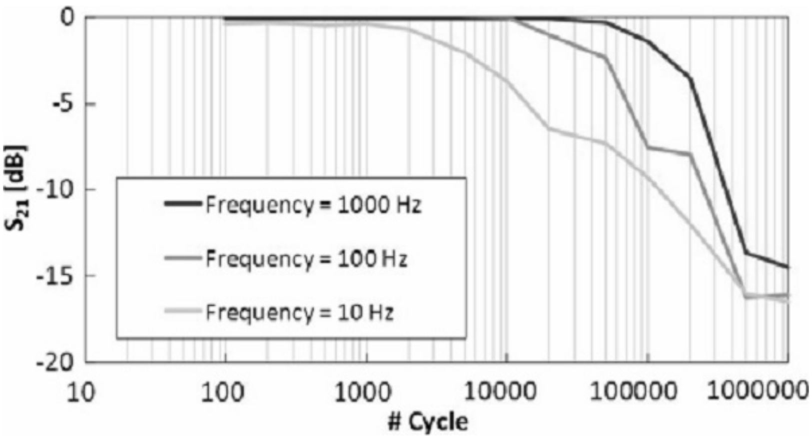

Fig. 6. Cycling tests performed at different frequencies. The charge trapping effect appears stronger at lower frequency than the one at higher frequency.

However, as shown in Figure 7, the actual lifetime of a device switched at lower frequency, is much longer that these used at higher frequency. The fact that scattering parameters degradation is much faster at lower frequency (in Figure 6) can be motivated as follow. Even though the duty cycle is kept at a constant value of 0.2, the stress voltage, and therefore the electric field, is applied for a longer time at a lower frequency. As a consequence, more charge is trapped and therefore the number of cycles tends to be smaller. Figure 6 and Figure 7 differs from each other for the horizontal axis expressed in number of cycle and time domain respectively.

From Figure 7 we can see that considering the same actuation time (i.e. the time in which the MEMS remain actuated) the device cycled at a higher frequency is subjected to a major number of impacts and hence the contact degradation occurs earlier than a device cycled at lower frequency.

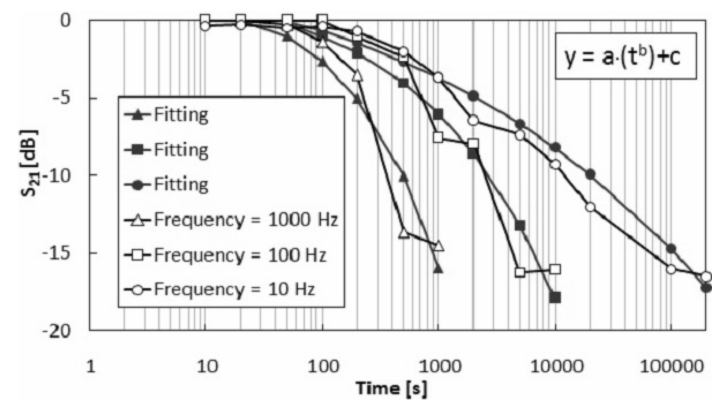

Fig. 7. Cycling tests performed at different frequencies. The picture show that at parity of actuation time in one period (duty cycle = 0.2) higher frequency due to a degradation of contact.

It is interesting to note that the slope of the S21 in Figure 7, can be considered as a degradation rate, and hence as a factor to evaluate the robustness of RF-MEMS: the faster the slope is, the easier and faster is the contact degradation. Power law curves (1) and stretched exponential law (2) were used to fit experimental data obtaining good results (see Figure 7 and Figure 8) like in [7] and [8].

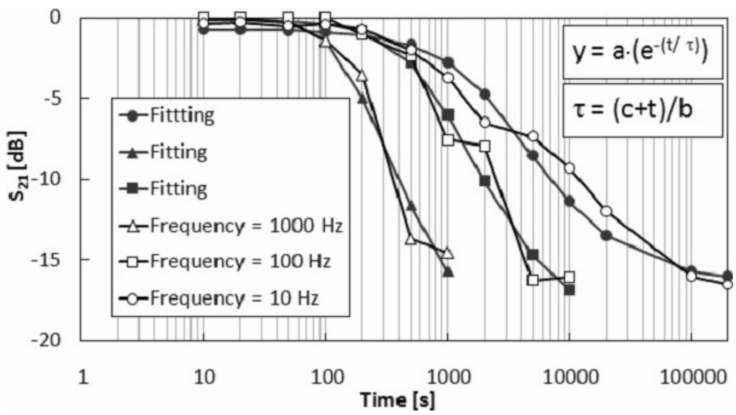

Fig. 8. Cycling tests performed at different frequencies. The picture show the fitting using stretched exponential law.

$$y = a \cdot (t)^b + c \quad (1)$$

$$y = a \cdot e^{-(t/\tau)}$$
$$\tau = (c+t)/b \quad (2)$$

The fitting parameters are shown in Table 1 for power law and in table II for stretched exponential law.

Table 1. Parameters used for fitting (power law).

	a	b	c
F = 1000 Hz	-0.3725	0.5639	2.36
F = 100 Hz	-0.6506	0.3747	2.65
F = 10 Hz	-3.499	0.1568	5.98

Table 2. Parameters used for fitting (exponential law).

	a	b	c
F = 1000 Hz	-1.7E-07	-18.67	17
F = 100 Hz	-0.07	-5.61	265
F = 10 Hz	-0.7	-3.15	1301

4. Conclusion

We discussed three different analysis methods and their effect on the RF-MEMS characterization. In particular we have shown how the pulse shape affects charge trapping phenomena. We have also shown that the effect of the temperature, associated with a specific cycling pulse, might only worsen the scattering parameters degradation instead of improving them.

Eventually, we proved that also different frequencies affect the results of cycles lifetime of a RF MEMS. These approaches and results here should be considered whenever RF-MEMS switches, especially those that suffer of charge trapping phenomena, are studied. Our approach allows users to focus on the final goal, which is to discover the actual performance of devices analyzed.

By knowing the effect that a measurement set-up induces in the MEMS performances, it is then possible to separate the induced parasitic behavior form the real device response. As already mentioned, the relatively low cycling robustness is a consequence of the measurements carried out on uncapped devices.

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