Methodology to assess the reliability behavior of RF-MEMS

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***ABSTRACT* — This paper reports on the investigation of the main phenomenon which limits the lifetime of capacitive RF MEMS : dielectric charging. To understand this effect, we have developed specific test set which measures the electrical (at both low and microwave frequencies) and electromechanical performances of RF MEMS to investigate their reliability. Several experiments have thus been performed such as DC bias stress and cycling under different actuation waveforms and environment conditions. These tests have shown that the dielectric charging creates a drift of the threshold voltages and we propose an appropriate figure of merit regarding the lifetime of capacitive RF-MEMS and a key parameter to determine the type of the failure which occurs.**

I. INTRODUCTION

In the last few years, lots of RF MEMS devices and circuits have been developed in labs and intensively published because of their attractive performances (low losses, good isolation and linearity) [1], [2]. Besides the high actuation voltages or packaging issue, the crucial problem that limits the manufacturing of such devices addresses their reliability behaviour. Indeed, many physical mechanisms can alter the lifetime of MEMS devices: mechanical creep effect, electromigration due to high current density, stiction through capillarity forces... But, in the case of an electrostatic actuated capacitive switch, the main cause of failure is the dielectric charging [3].

Even if this phenomenon is not yet totally understood, we can suppose that charges can tunnel into the dielectric and become trapped on the surface and in the volume of the dielectric. The trapped charges create a parasitic field which can have two consequences: the stiction [4] and the screening of the bridge. In the first case, the upper membrane remains in the down position even if the actuation voltage is released. In the second case, the bridge is in the up position whereas a voltage is applied. In both cases, it is important to outline that the signature of this mechanism is a drift of the pull-down and the pull-up voltages [5].

This paper focuses on the causes and consequences of the dielectric charging in capacitive RF-MEMS and proposes an appropriate characterization methodology to assess the reliability behaviour of RF-MEMS. It will be organized in two sections. The next section will address the test set we have developed to investigate the reliability behaviour of the devices as the last section will present the obtained results and the discussion.

II. INSTRUMENTS AND METHODOLOGY

To study the dielectric charging effects, we have developed specific test set both at low and microwave frequencies in order to study the functioning of RF-MEMS as a function of time.

II.1 Low frequency test setup

The first proposed ELectrical Test set (ELT) system (Figure 1), which has been developed at IMEC [6], is a low frequency measurement set-up. The system can detect the main features of the switch (cycle pull-in voltage, rise- and fall-time of the switching action, difference between the on-capacitance and the off-capacitance ∇C for capacitive switches or contact resistance for ohmic switches, and a drift in any of these parameters). Such switches are typically driven by a DC actuation signal (as from generator 1 in Figure 1) that causes the metallic bridge of the switch to move down. The ELT system uses a frequency of 10.7 MHz (generator 2 in Figure 1) superimposed on the actuation signal. The combined signal is applied to an RF-switch board containing a number of RF-MEMS switches. Because the RF MEMS switch is part of a voltage divider, the carrier voltage is modified by the switching action, resulting in an amplitude modulation containing the necessary information of the features of the switching action. After passing through a multiplexer, which is used to select one switch a time for monitoring, a buffer sends the by now amplitude modulated 10.7 MHz signal to the detection stage.

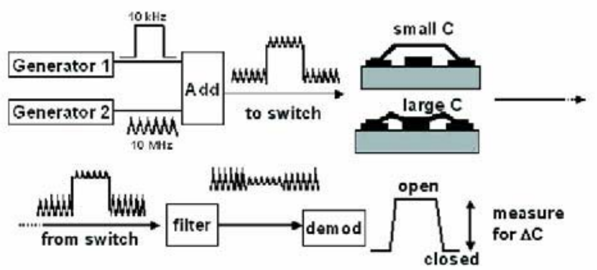

Figure 1 : ELT set-up for the case of an RF-MEMS capacitive switch.

Figure 2 shows a typical output signal of the ELT system for one switching event of a RF-MEMS capacitive switch. The amplitude is directly related to the change in capacitance during switching, one can also see the rise and fall time, giving information on the switching speed. Similar information can be obtained for ohmic contact switches (changes in contact resistance). By monitoring such signals constantly during electrical or environmental stressing of the MEMS switches, one can perform reliability tests and obtain information on the lifetime of the switch for different conditions, i.e. perform reliability testing.

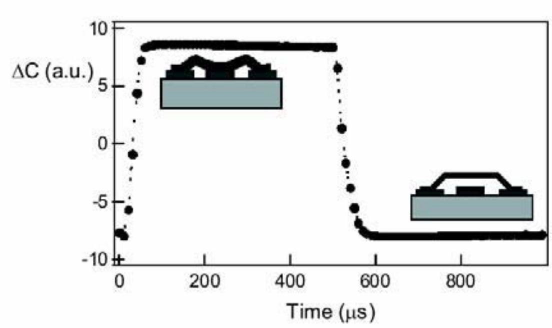

Figure 2 : Typical output signal of one switching event of a capacitive RF-MEMS switch using the ELT system.

II.2 Microwave test setup

An other proposed Test set up, developed at LAAS-CNRS [7], involves a Vector Network Analyser (Figure 3) to directly monitor the degradation of the microwave performances of RF-MEMS devices under investigation.

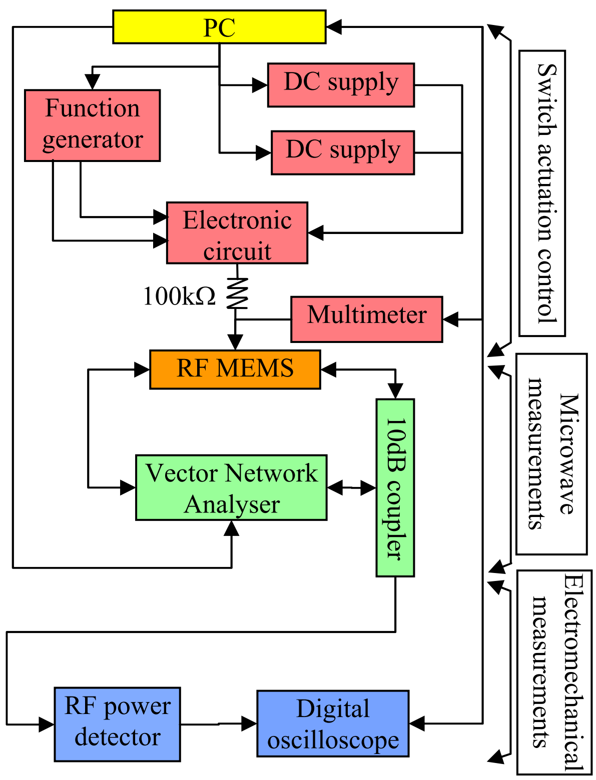

Figure 3 : Block diagram of the reliability test set

The test set is divided into three parts. The first one controls the switch actuation and uses a function generator, two DC supplies and an in-house commutation electronic circuit. At the output of the electronic circuit, we obtain a fully programmable signal whose voltage can vary between -100V and +100V, with frequency ranging from 1Hz to 50MHz. Finally, a multimeter is monitoring an eventual dielectric breakdown.

The second part of the test set concerns the microwave performances measurement of the switches and then its reliability. This is realised through a vector network analyser (VNA) which operates either in CW power source either in S parameters measurement.

An RF power detector associated with a digital oscilloscope constitutes the third part of the test set which measures the electrostatic performances of the switches. Indeed, at the output of the detector, a DC voltage is measured and is the image of the state of the bridge. The switching time can be known measuring the time between the two voltage values.

We can observe in this block diagram that all the measurement sets are controlled by a PC through an HPIB bus and fully automated thanks to a software which allows choosing between several types of test.

II.3 Environmental testing [8]

Reliability is defined as the probability that an item will perform a required function (which is monitored by the previously presented test set) under stated conditions for a stated period of time. Such conditions can be electrical or environmental. For example one has to test the performance during thermal cycling, during hot or cold temperature storage, in the presence of high humidity and temperature, in the presence of gasses, during externally applied vibrations, after shock events…

It is for example of importance to study the behaviour of MEMS systems with moving parts as a function of the humidity of the environment to study the effect of capillary forces on stiction of the MEMS. An instrument, used by both CNES and IMEC for MEMS tests and reliability studies, has been developed. It is a small chamber, in which the MEMS can be mounted and electrically activated (DC only). The humidity can be changed from about 3 to 95% RH within a temperature range of 15 – 40 °C. Optical monitoring is possible through a small window and it is then possible not only to measure the behaviour of the MEMS electrically, but also to monitor its movement optically.

Other crucial parameters which drive the RF-MEMS reliability are the gases and temperature environment. These parameters have to be controlled during the reliability investigations and their impacts on the lifetime of the tested devices have to be determined. For this purpose, IMEC purchased the so-called PAV-system (Süss-Microtec), which is shown in Figure 4. This system consists of a vacuum chamber with a thermochuck (-10 to +150 °C) and probes. It allows the testing of MEMS on wafer level, with DC and for RF signals applied, for different temperature, gasses and pressure. An optical system can be mounted on top of the system such that the MEMS can also be monitored optically.

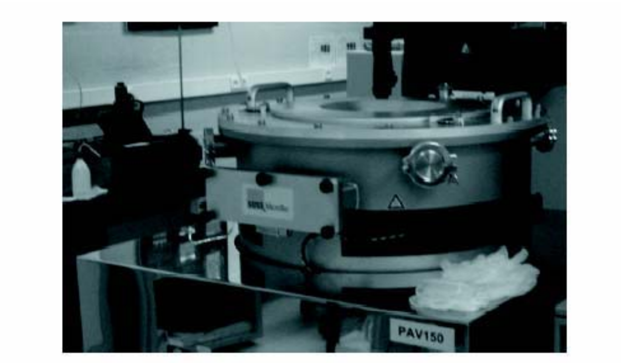

Figure 4 : Vacuum probing system for reliability testing of MEMS.

In addition to humidity, vacuum, temperature and gasses, also radiation tolerance, chemical exposure effects, biocompatibility, the effects of extreme temperatures and shock and vibration might have to be studied for MEMS. Also this requires dedicated instrumentation.

III. Results and Discussions

The main problem with capacitive RF MEMS is the charge injection within the dielectric. The nature of these charges and their migration are not presently very clear, but the consequences like stiction and screening effects can be observed. So we need first a better understanding of the dielectric charging effect and then an accurate modelisation of such phenomenon.

III.1 Failure Phenomena due to dielectric charging [7]

Different tests have been performed in order to evaluate the consequences of charging on pull-down and pull-up voltages. This has been conducted through an evaluation of the microwave performances degradation during cycling.

A capacitive RF MEMS was cycled with a frequency of 5Hz and with a positive bias of 27V. We have monitored the S_{21} parameter at 20 GHz for the up and down positions every 1000 cycles up to 1 million cycles. Figure 5 shows microwave performances vs the number of cycles.

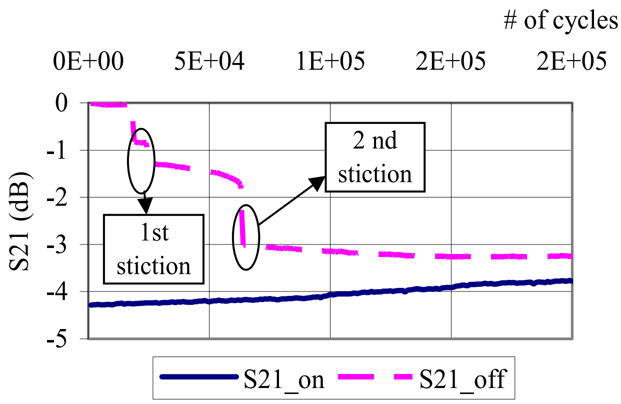

Figure 5 : S_{21} parameter at 20 GHz (on /off state) versus the number of cycles

The curves show different regions. We can notice that there are two stiction regions. The first one occurs after 30000 cycles and corresponds to the decrease of the up-state S_{21} parameter from -0.2dB to -1.4 dB. The second one occurs after 70000 cycles and corresponds to the decrease of the up-state S_{21} parameter from -1.4dB to -3.2dB. In Figure 6 is reported the S_{21} parameter at 20 GHz versus a voltage sweep performed after 70000 cycles. The dotted curve shows that the negative pull-up voltage crosses 0V leading to a partial attraction (S_{21}= -3.2dB) of the bridge when no actuation voltage is applied.

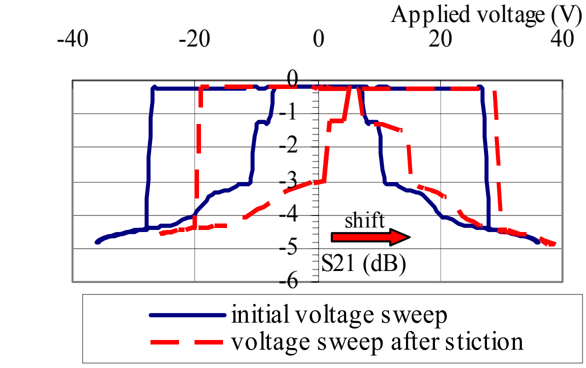

Figure 6 : S_{21} at 20 GHz versus voltage sweep after 70000 cycles

We have performed the same test in another type of switch. The cycling frequency was 5Hz and the applied voltage was 60V. The S_{21} parameter vs the number of cycles demonstrates that the degradation mechanism is now the screening effect. It occurs after 100000 cycles and corresponds to the increase of the down-state S_{21} parameter from -7.5dB to -2.8dB. After this screening effect, a voltage sweep with S_{21} measurement has been carried out and the results are shown in Figure 7.

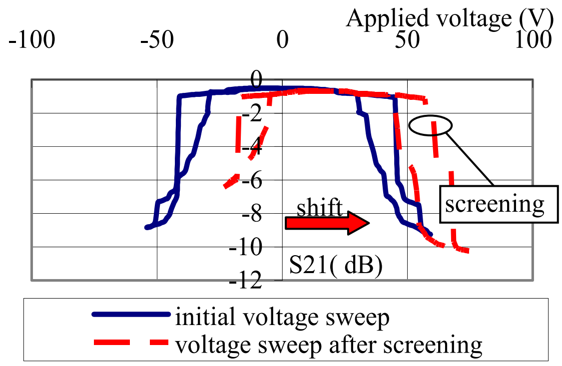

Figure 7 : S_{21} at 20 GHz versus voltage sweep after 100000 cycles

The dotted curve shows that the positive pull-down voltage crosses 60V before the negative pull-out voltage crosses 0V, leading to a screening effect rather than a stiction effect.

This demonstrates that a key parameter to know which between the screening or the stiction effects is going to occur the first, is the difference between the pull-down and the pull-up voltages, and the difference between the pull-out voltage and 0V.

III.2 Impact of cycling frequency on reliability behavior

As stated before, charging is the most commonly encountered reliability problem in RF-MEMS switches. We have already demonstrated that the commonly quoted number of cycles to failure is not a good measure of the reliability of switches suffering from charging [6]. Switches prone to stiction due to charging were actuated with different frequencies and duty cycles and we have showed that the number of cycles to failure is severely affected by the actuation frequency and duty cycle. If the failure is purely due to charging, the contact time (down position gives rise to charge injection) should be equal for all. Figure 8 shows that this is indeed the case.

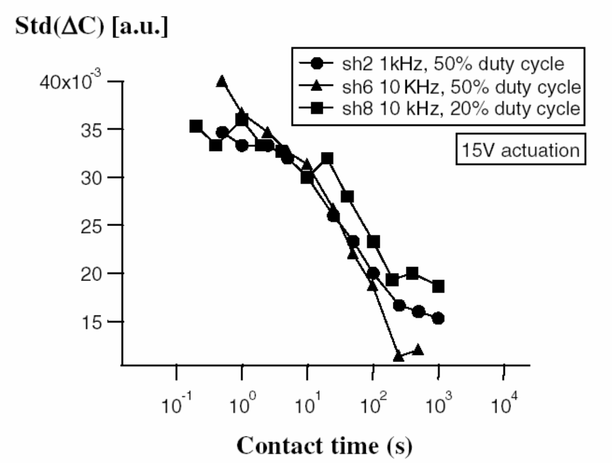

Figure 8 : The contact time of the switches is the same.

The 20% duty cycle switch lives a bit longer. This is explained by noting that the time to be actuated from the off- to the on-position is a significant part of the actuation time for this switch. These graphs show clearly that the commonly quoted number of cycles to failure is not a representative figure for the switch reliability. The total actuation 'down' time is a much better figure of merit.

We have then performed DC bias test experiments in which the switch is continuously in its down state. The stress procedure consists in applying a DC voltage on a switch in the down state position. Then, periodically we perform microwave measurements (S_{21} at 20 GHz) for a voltage sweep ranging from -V to +V in order to determine the MEMS threshold voltages.

We have first applied a positive bias stress during 30min, then we have measured the S_{21} vs the voltage sweep. Consequently, we have applied a positive bias stress during 30min again and another voltage sweep with S_{21} measurement has been done. The results are presented in Figure 9.

We can observe a positive drift of the threshold voltages which is relevant with the presence of a dielectric charging as we have previuously observe during the cycling tests.

We have finally demonstrate the equivalence between DC and cycling test regarding the Figure of merit proposed by IMEC : the time the switch spends in its down state which leads to failure is the same in the two cases. This suggests that the DC stress is an efficient way to assess the reliability of capacitive RF-MEMS.

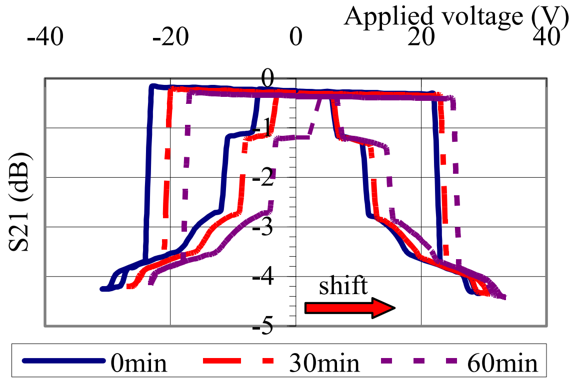

Figure 9 : S_{21} at 20 GHz vs voltage sweep for 30min and 60 min positive DC stress duration

IV. Conclusion

This paper presents some instruments and methodologies to assess the reliability of RF MEMS. Different test set up have been presented which permit to monitor the functionality of RF-MEMS both in low and microwave frequencies and under different electrical and environment stresses.

We have performed several types of experiments: DC stress and cycling with different frequencies and ambient condition and demonstrate that the appropriate figure of merit is the time the switch spends in its down state. We also outline that the values of the threshold voltages compared with the applied ones drive the failure type: stiction or screening.

Acknowledgement

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