The reliability of RF-MEMS: failure modes, test procedures and instrumentation

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ABSTRACT

This paper discusses some reliability issues that play a role for capacitive RF MEMS switches. We describe how these degradation mechanisms affect the functioning of the switches. Also the methodology that can be used to test capacitive RF MEMS switches, including some packaging aspects, and dedicated instrumentation required to perform these tests are discussed.

Keywords: RF-MEMS, reliability, failure analysis, measurement techniques

1. INTRODUCTION

MEMS technology is successful for several applications such as for example accelerometers, pressure sensors, digital mirrors and inkjet printheads. Still, it turns out for many MEMS, that putting them into large-scale products is more challenging than expected and that the time to marked takes longer than predicted. One of the main reasons is the reliability if these devices. Reliability is often only the very last step that is considered in the development of new MEMS. The early phases are dominated by considerations of design, functionality, and feasibility; not reliability. An important reason for missing reliability data is that in view of the use of new materials and processes, the material data, the know-how on failure modes, the means and the procedures to perform reliability tests and consequent failure analysis are often not present or unknown. Another reason for missing reliability data is that almost all publications on MEMS reliability are focused on a certain specific microsystem and can mostly not be used for another application.

Typical MEMS systems for which this is the case are RF-MEMS [1,2]: reliability is one of the main issues hindering the conversion of these devices from lab prototypes to operational systems [1,3-5]. RF MEMS switches are small devices that use mechanical motion to toggle RF signal transmission between on and off. They are developed for RF switching, tunable capacitors and adaptive impedance matching, this for use in base stations, anti-collision radars for automotive, GPS, WLAN, mobile phones, phase shifters for satellite-based radars, satellite communication systems etc. They are of interest to advanced RF systems because they promise a lower loss, higher linearity and broader bandwidth compared to traditional semiconductor switches such as varicaps (pn-diodes), pin diodes and GaAs field effect transistors (FET). For this reason, they are sometimes called the ‘next killer MEMS’. In addition, they allow for more miniaturization. Cost savings are expected because they allow for planar integration. For example inductors, tunable capacitors and other components can be fabricated on the same substrate. A market study (Nexus) showed that at this moment more than 100 institutes and companies worldwide are involved in RF MEMS design and development.

Ohmic switches	*Capacitive switches*
- contact degradation - contact contamination - stiction due to welding - stiction due to capillary forces (humidity) - buckling of the bridge due to stress gradients or temperature effects - creep - electromigration	- charging of the insulator causing shifts in the pull-in and pull-out voltage and stiction - stiction due to capillary forces (humidity) - buckling of the bridge due to stress gradients or temperature effects - creep - electromigration

Table I: Reported and expected reliability issues and failure modes for RF-MEMS switches

Reliability, Testing, and Characterization of MEMS/MOEMS III, edited by
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The reliability of RF-MEMS is reported to vary between 1 and 10 billion cycles. Some applications require only one switching event, others more than 200 billion. Although mature MEMS switches are reported on in literature, long term reliability has not really been addressed yet. Reported [3,6] and expected reliability and failure issues are listed in Table I for metal-to-metal contact switches (ohmic) and capacitive switches. We will discuss some of them in some more detail in this paper. Also the packaging of the RF-MEMS is an important issue helping to improve the reliability. It is preferable that these devices are packaged at the wafer level, in a low humidity hermetic package. Packaging is at the moment still the most expensive part of the RF-MEMS. The effect of packaging on functionality and reliability of the switches is also still an issue of concern.

There exist two basic forms of RF-MEMS switches: the metal-to-metal contact switch (ohmic) and the capacitive switch. In ohmic switches, the metal of the bridge makes direct contact to the metal of the waveguide. The major problem for resistive switches is contact degradation and contamination [1]. In this paper, we will limit the discussion to capacitive RF MEMS switches. Figure 1 shows a schematic drawing of a capacitive metal RF-MEMS switch. It consists of a metal bridge that spans the centre RF transmission line of a coplanar waveguide. The latter consists of three lines: an RF transmission line centred between two ground plates. When the bridge is up, the capacitance between bridge and RF transmission line is very low and the RF signal passes without much losses. When a DC voltage is applied between the RF transmission line and the bridge, the bridge is pulled down until it touches a dielectric isolation layer. The large capacitance thus created shortens the RF signal to the ground. A SEM photograph of such a switch is shown in Fig. 2.

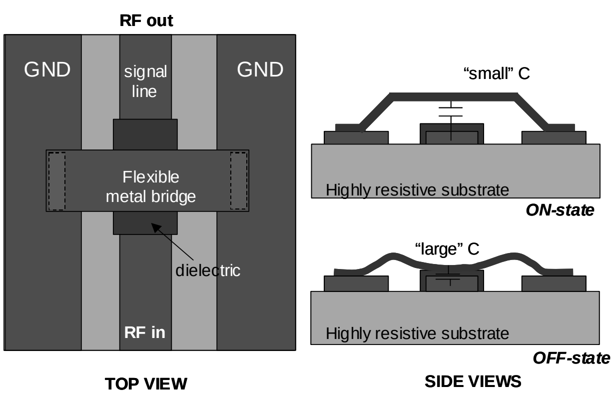

Fig. 1. Schematic picture of a capacitive RF-MEMS switch.

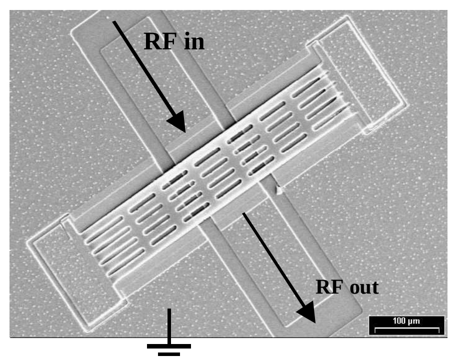

Fig. 2. SEM photograph of a RF-MEMS capacitive switch. From [7].

2. TESTING AND FAILURE

2.1. Capillary stiction

A very well known failure mode in MEMS is stiction, i.e. microscopic surfaces contacting each other may be kept together due to capillary condensation, molecular van de Waals forces or charging effects. If the restoring forces in the bridge of the switch are not large enough to pull the bridge up again after the actuation voltage has been removed, the device fails due to stiction. An important cause of stiction is capillary induced stiction. Fig. 3 shows a model predicting such a stiction as a function of the restoring force of the bridge, the environmental humidity and the roughness of the surfaces [8, 9]. The data points were taken from [10]. This model shows clearly that the probability to have stiction due to capillary forces increases if the restoring force of the bridge decreases and if the surface roughness decreases. The surface roughness of a bridge can easily be measured using atomic force microscopy (AFM). In most cases the roughness of the top surface of such a bridge is not necessary the same as the one of the bottom surface, as shown in the AFM measurements of a bridge composed of an Al-alloy (Fig. 4). In order to measure the bottom side, the bridge was simply removed using scotch tape. The bottom surface was found to be much smoother than the top surface, increasing the risk for capillary induced stiction. Stiction due to capillary forces is an important problem for RF-MEMS switches.

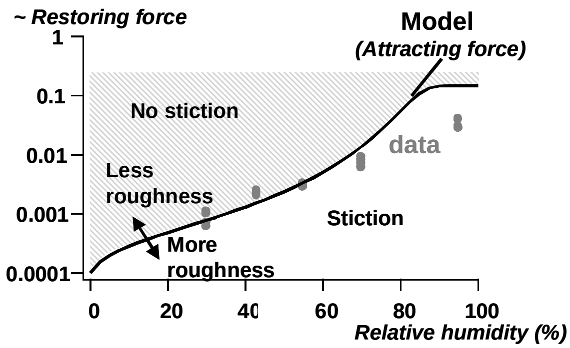

Fig. 3. Model predicting stiction as a function of restoring force (a.u.), humidity and roughness [from 9].

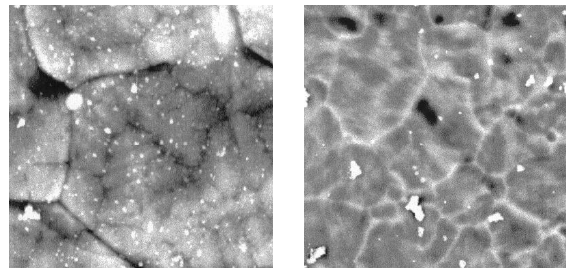

Fig. 4. AFM data of the Al-alloy bridge of an RF MEMS capacitive switch. Left: measured on the topside, mean roughness = 34 nm. Right: measured on the back side, mean roughness = 8 nm. The measurement area is 15 µm x 15 µm for both.

2.2. 0-level packaging

Humidity induced stiction can be avoided by packaging the switch in a moisture free environment, for example through the use of a 0-level package. This can for example be a Si or glass cap that is locally placed over the RF-MEMS on wafer level, using an hermetic sealing ring. A picture showing such packages is given in Fig. 5. This encapsulation is in general done prior to dicing because standard wafer sawing will if not destroy the device, at least introduce particles that can lead to failure. Hermeticity testing of cavities (fine leak and gross leak) is in general done using standard methods (i.e. MIL-STD-883D). However, because the cavities of such RF-MEMS packages deal with volumes that are much smaller (at least 1000 x) than the ones described in the MIL standard, the standard test techniques are not applicable [11, 13]. The upper detection limit of the fine leak tests was shown to be well below the lower limit of the gross leak test, leaving a gap in the detection region of these two techniques. Leaky cavities can in this way still escape from detection with these standard techniques. Jourdain et al. [12] showed that this detection gap can be bridged through the use of microbolometers and MEMS resonators. De Moor et al. [13] showed that the alternative procedure for testing, as depicted in Fig. 6, can also offer the required information.

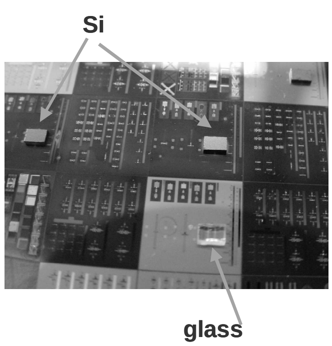

Fig. 5: Glass and Si caps used for 0-level packaging of capacitive RF-MEMS on wafer level [12]

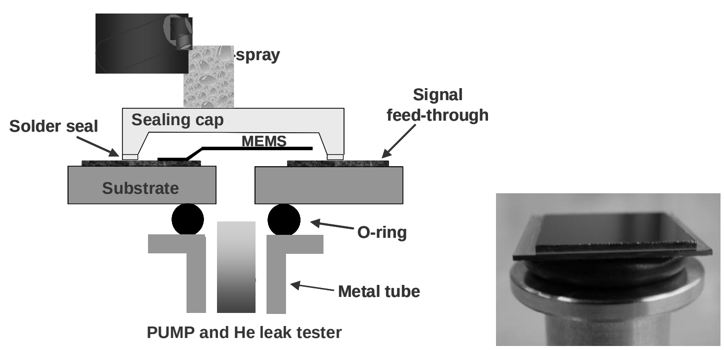

Fig. 6: Procedure to test the hermeticity of 0-level packages for RF-MEMS [13]

2.3. Charging induced stiction.

A more important cause of stiction encountered in RF-MEMS switches is stiction due to charging of the dielectric. Charging is caused by the high electric field that is present across the dielectric of the capacitive RF MEMS when the bridge is pulled down and touching the dielectric. Because the pull-in voltages required for bridge actuation are in general rather high, typically in de order of 10 to 30 V, field strengths in the order of MV/cm can be encountered during normal use. This results in currents through the insulator due to Fowler-Nordheim tunnelling, Shottky injection or Poole-Frenkel conduction. As a result trap generation and charging of existing traps in the dielectric cannot be avoided. The accumulated charges result in a change of the pull-in and the pull-out voltage of the bridge, directly affecting the behaviour of the device. Actually, this parasitic charging of the dielectric is clearly the most important failure mode in capacitive RF-MEMS switches. When actuated under normal conditions, i.e. in ambient air with a unipolar actuation waveform, the switches typically fail due to this effect. An example of this is shown in Fig. 7. This figure shows a measure for the change in capacitance during switching of a capacitive RF-MEMS switch (Al-alloy bridge, SiN dielectricum) as a function of the number of switching cycles. The measurement is performed using the in-house called ELT, Electrical Lifetime Test system, as will be explained further on. The switches are actuated at 20V, 1kHz using a unipolar actuation waveform. They work perfectly, i.e. they have a stable capacitance until about 10^6 cycles when they fail (capacitance decreases). Optical observation of the switches, using the in-house called MOPS system (explained further on) indicate that the switches indeed fail due to stiction. C-V measurements before and after failure confirm that this is charging induced stiction: the curves typically shift towards higher voltages. Also the fact that one day later, the switches typically work again confirms that the stiction is caused by charges in the dielectric that flow away when the bridge is not in down position. A further proof for charging effects is given in Fig. 10.

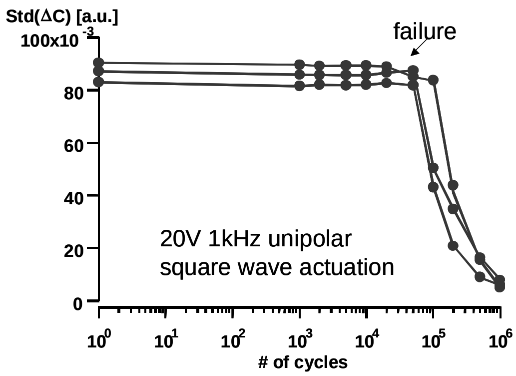

Fig. 7: Standard deviation of the output of the ELT detector (i.e. measure for DC) as a function of the number of switching cycles for 3 similar capacitive RF-MEMS [14]

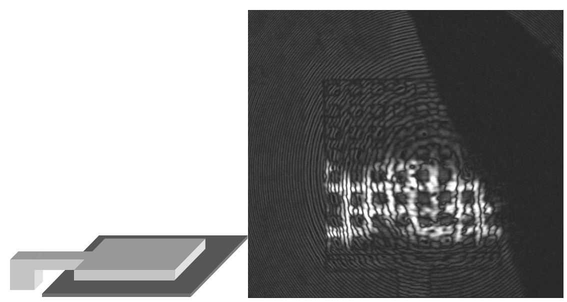

Fig. 8. Left: schematic showing the lay-out of the switch. Fixed part at the left. Right: MOPS difference image. The fixed part of the switch is at the bottom. The switch is still moving in the 'white' area. There is stiction at the top side (right side in the left fig.) of the switch.

There are several solutions proposed for this problem. The most common one is using an alternative actuation waveform, some examples are shown in Fig. 9. One alternative is to start at a high voltage to pull-in the switch but keep a low voltage for the remainder of the time, indeed a lower voltage is required to keep a bridge down than to pull it in. In the second a burst of alternating plus and minus voltage pulses is used. The pulse frequency is high enough to keep the bridge down during the burst. The main purpose of such waveforms is to avoid charging of the dielectric and they clearly result in much higher reliability data (higher number of switching cycles before failure). Another solution is to improve the dielectric in such a way that it is charging resistant. Although still a lot of research is going in this direction, it turns out to be fairly difficult to make good dielectrics for metal RF MEMS switches. In fact, it has been proposed to make the dielectric worse, by adding impurity atoms so that the overall conductivity of the dielectric becomes so high that the charge in the traps flows away fast after turning off the actuation voltage [16]. A third solution is to prevent that the actuation voltage drops across the dielectric by adapting the design of the switches.

An important note is that the number of cycles a capacitive RF-MEMS survives in not a good figure for the reliability of these devices if one not also mentions the frequency at which the switches were activated and the duty cycle [18]. If one studies the same kind of switch at a higher switching frequency or at a duty cycle where the switch is a shorter time down than it is up, its lifetime seems to be better (Fig. 10, left). If we plot however the measurements as a function of the time the switch is is down position (Fig. 10, right), we clearly see that the all follow the same curve and have the same lifetime. The lifetime in the downstate is for this reason a better figure for the reliability of these switches than the number of cycles they survive. This effect also confirms that charging of the dielectric is indeed the reason for failure of the switches.

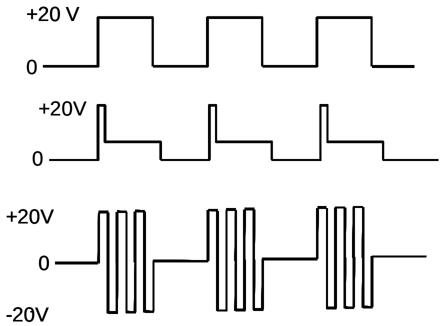

Fig. 9. Some typical actuation forms. Top: normal waveform inducing charging of the dielectric. Center and bottom: alternative waveforms used to reduce the charging.

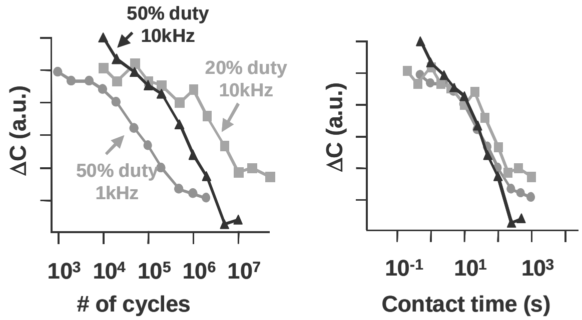

Fig. 10: Left: Dependence of the number of cycles up to failure of an RF-MEMS capacitive switch on the frequency and duty cycle. Right: Same data plotted as a function of down time.

2.4. Electrical lifetime measurement system (ELT)

The experiments shown in Fig. 7 and Fig. 10 were performed using the Electrical Lifetime Test system [15] developed at IMEC by W.M. van Spengen (patent filed). The principle is explained in Fig. 11. The ELT detects the amplitude modulation of a 10 MHz carrier that is superimposed on the actuation signal. This modulation is caused by the capacitance change of the switch. A typical detector output signal when a switch is actuated with a square wave is given in Fig. 12. This system allows a very sensitive measurement of the switching induced capacitance change, ΔC, of an RF-switch during reliability tests. It can also be used to test the changes in contact resistance of ohmic switches using a similar principle. It also allows measuring the pull-in and pull-out time of a switch. In order to detect also changes in the latter, we typically plot the standard deviation of the output signal of the ELT detector in figures such as Fig. 7 instead of the amplitude of this signal.

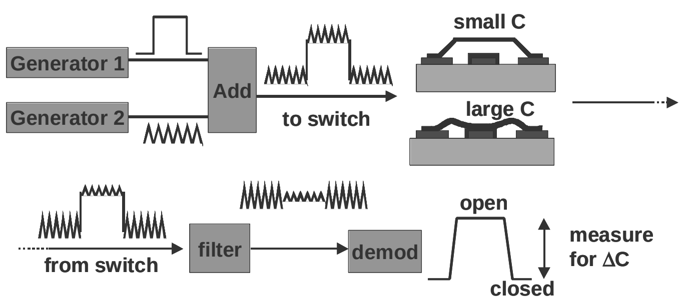

Fig. 11: Principle of electrical lifetime test system (ELT) for RF MEMS switches (patent filed).

Fig. 12: Typical output signal of the ELT system. The amplitude is a measure for the change in capacitance of during switching. The slopes can be used to determine the switching speed (see Fig. 16).

2.5. MEMS optical system (MOPS)

It is very useful to combine electrical measurements, such as from the ELT system, with optical observation of the MEMS. This often helps to determine the failure mode and cause. The instrument we use is called in-house ‘MOPS’ (Mems Optical System) and was described in [19]. It consists of a dedicated interferometer, acquisition and control electronics and is based on the Optonor Micromap 5000 interferometric system (Fig. 13, right). This instrument allows to image in-situ small (max. 80 nm) out of plane vibrations of structures with a 3 nm resolution for frequencies up to 15 MHz. Slow movements (<10 Hz) can be investigated over a range of a few µm with a resolution of about 10 nm. The system can monitor the movement of a device directly, or detect the movement of a certain part of a device with respect to another fixed reference part. The latter is shown in Fig. 13. The left shows an optical image of a RF-MEMS capacitive switch. An image of a moving switch where the applied voltage is below the pull-in voltage, resulting in an asymmetric movement of only the center part of the switch, is shown at the center in Fig. 13. This image shows only changes in displacement. Also the picture shown in Fig. 8 was taken in this way with the system. However, also movies of working switches can be made. Fig. 14 shows some consecutive images of a movie taken with the MOPS system on a moving MEMS relay. The relay is fixed at the bottom side. The movement clearly shows some anomalies in the MEMS.

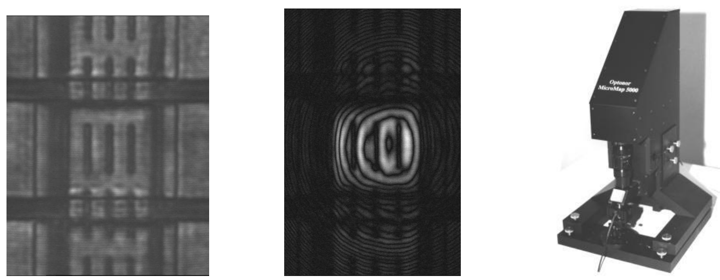

Fig. 13. Right: Photograph of the MOPS system. Left: Optical image of switch, center: image showing that the center part of the switch moves.

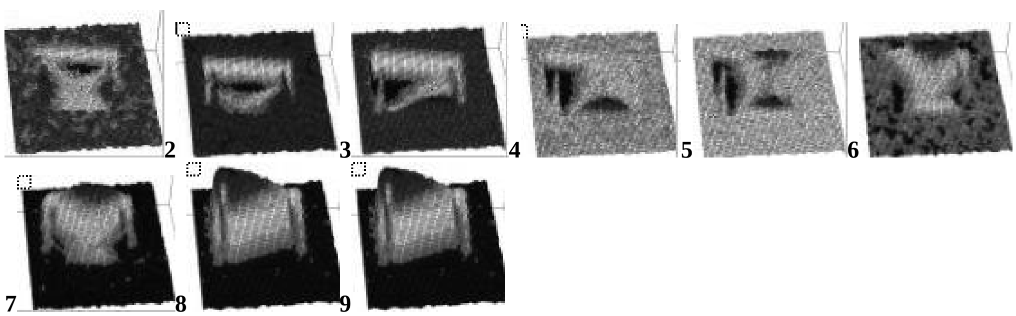

Fig. 14: Sequential pictures taken from a moving defective micromachined relay vibrating at 1000 Hz, using MOPS.

Optical systems such as the MOPS allow correlation of electrical results with failure modes such as stiction, partial stiction: i.e. one part of a bridge is still moving while the other part is stuck, and anomalous movement: ex. upon applying a voltage to a buckled bridge, the edges of the bridge touch the dielectric first and the remaining part follows later. This combination of electrical and optical measurements is very important for a correct interpretation of the failure mechanisms of these switches.

2.6. Test chamber

In order to test RF MEMS in depth, it is mandatory to measure their performance during switching with RF signals applied. It should also be possible to do this at different temperatures and pressures (ex. for space applications), and in different environments, while also optically monitoring the MEMS. This is possible by using a test chamber such as for example the PAV150 environmental chamber (Suss-Microtec). This chamber was specially adapted for the reliability study of MEMS, specific for RF MEMS. Fig. 15 shows a layout of the chamber and a photograph. It consists of an environmental chamber and a thermochuck (-10 to +150°C). Operation is possible to $2 \cdot 10^{-5}$ mbar or any pressure between this level and atmospheric pressure. Four DC and four RF probes can be placed inside the chamber. The system can be purged with for example nitrogen to test devices in a controlled environment.

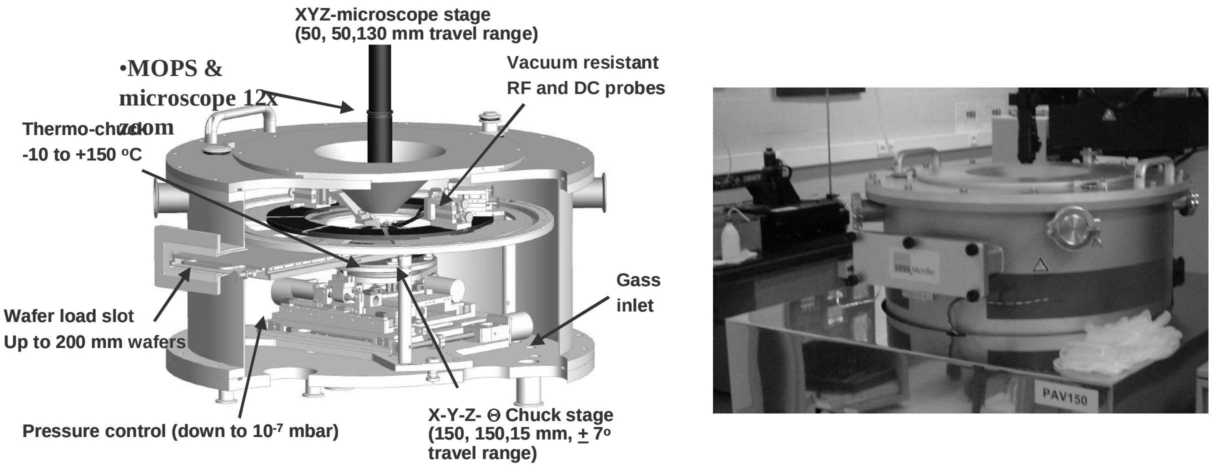

Fig. 15: Test chamber for RF MEMS reliability testing. Left: schematic showing the different features, right: photograph of the system.

Fig. 16 shows the result of an experiment performed on a RF MEMS capacitive switch in the PAV system at different pressures: atmospheric pressure and vacuum. The ELT system was used to measure the change in capacitance during one switching cycle. In control conditions (atmospheric pressure) one can see that the capacitance increases upon actuation and decreases when the actuation is removed. The on and off time can be obtained from the slopes of this curve. In vacuum the switch moves much faster, which can be deduced from the steeper slopes. In addition, a fast variation of the capacitance is seen when the switch is released. This is due to the lack of damping in vacuum, causing vibrations of the bridge when it is released.

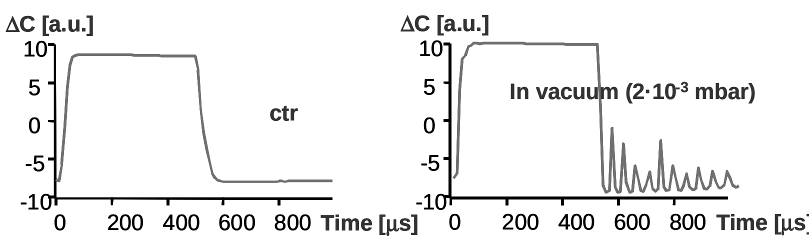

Fig. 16: Change in capacitance upon actuation of a capacitive RF MEMS (25V, 1kHz, 50% duty cycle) in atmospheric pressure (left) and in vacuum (right).

3. CONCLUSIONS

In this paper we described some reliability and failure analysis issues of RF-MEMS capacitive metal switches. Issues such as capillary and charging induced stiction, 0-level packaging, electrical lifetime testing, optical motion investigation and test chambers were discussed. It is shown that dedicated techniques are required to study RF-MEMS, such as instrumentation for electrical lifetime testing and for monitoring of the movement of the switches, and special test chambers. We showed that the combination of electrical lifetime measurements with optical motion measurements provides important information on the reliability behaviour of the switches. The main failure mode of the investigated switches is stiction, caused by charging of the dielectric. This failure mode can be circumvented through the use of alternative actuation waveforms. Issues that were not discussed in this paper are creep, stress and electromigration.

Creep can be expected to become an important reliability problem, especially for Al-based metal bridges and at high RF power, where the temperature in the bridge might well increase to creep sensitive levels. This can cause a deformation of the bridges and changes in pull-in and pull-out behaviour. Processing induced stress can cause buckling of the MEMS bridges. This can be optimised through the use of test structures such as cantilever beams, Guckle structures etc. [20]. A larger problem is related to the packaging of these devices. If the packaging process involves high temperature steps, this might well induce deformation of the beams due to temperature induced material changes in the metal bridge.

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