Project "Avoidance MEMS Dielectric Charge Trapping"
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Executive Summary Report

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1) Definitions - dielectric charging and RF-MEMS

RF-MEMS micro scale relays that are using electrostatic actuation in order to open or close a metal to metal contact, or sharply increase an RF capacitance. This result in a sharp variation of the RF impedance of the device, and it permits to route RF signals from one port to another, or change the resonance frequency of a microwave filter for instance.

Electrostatic actuation is the most popular actuation for RF-MEMS because its current consumption is very low very low, resulting in near zero power consumption. On the RF side, this type of actuation is relatively easy to implement into microwave circuits.

The basics of this type of actuation are depicted below. Most MEMS devices are using parallel plate electrostatic actuators.

In these devices, an attractive mechanical force is generated by electric charges the two parallel plates of a MEMS actuator. On a MEMS actuator, one of the two plates is moveable, and can be deflected towards the fixed plate The electrostatic force, Fe, is given by the following relation:

$$Fe = \frac{1}{2} C V^2$$

where C is the capacitance of the actuator and V is the applied voltage across the electrostatic gap.

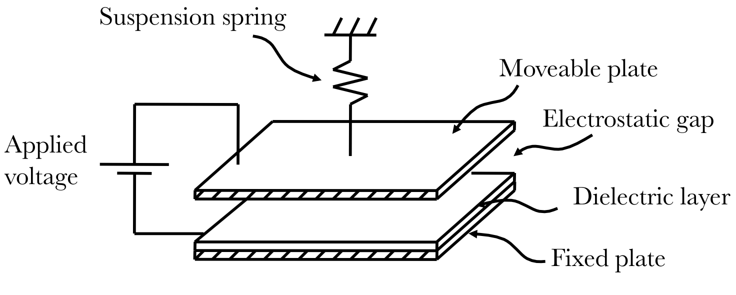

Figure 1 - Schematic of a parallel-plate electrostatic actuator

The suspension spring generates a force that opposes to the electrostatic force, and solving the system for equilibrium comes to the following Capacitance-Voltage characteristic:

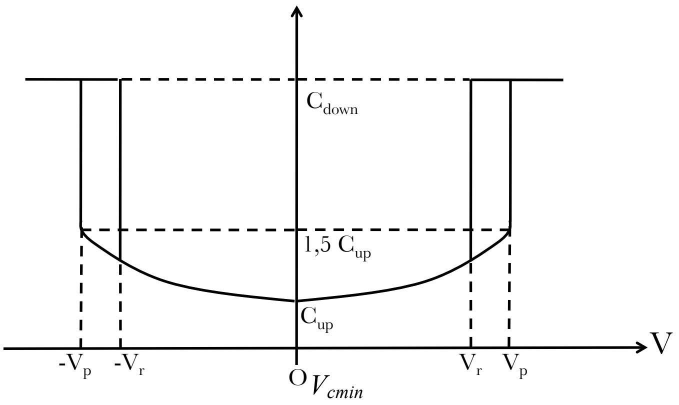

Figure 2 - Ideal capacitance to voltage characteristic

Since the electrostatic force is a strong non-linear function of the separation gap, the device has hysteresis, and the voltage that permits to close the gap is different from the voltage needed to release the plate in the up state. These voltages are V_p and V_r the pull-in and release voltages respectively. These voltages are related to the amount of charges stored on the plates of the actuator, and the generated forces.

Another important characteristic of the device is the V_{cmin} voltage, which is the voltage for which the capacitance is minimal. This voltage is normally zero.

Typically, RF-MEMS devices are pulled down around 50 Volts, and their initial capacitance is a few tenths of picoFarads. The total amount of charge required for pull-in is therefore in the order of $50.10^{-13} = 5.10^{-12}$Coulomb, which is very low. There is no current leakage and this is why electrostatic actuators are so low power; but the low power nature of this actuation makes it very sensitive to small perturbations. Indeed, requiring extremely low current means also that only a very small amount of change in electrical charge distribution in the circuit induces a significant deformation of the mechanical structure of the device.

In many devices, the capacitance variation is sharp and the actual RF transmission through the capacitance to voltage is close to the figure below:

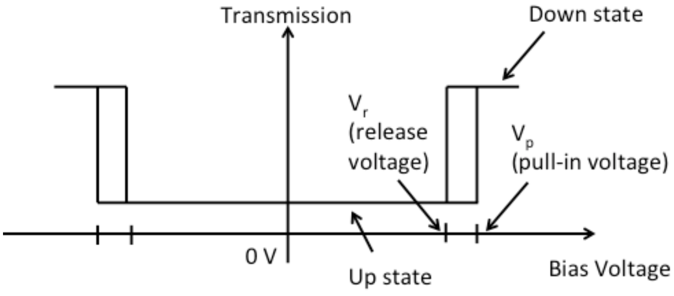

Figure 3 – Typical C(V) characteristics of an electrostatic actuator.

These capacitance to voltage characteristic are all ideal, but problems start appearing when electrical charges remain trapped either inside a dielectric layer in the actuator, or inside the substrate.

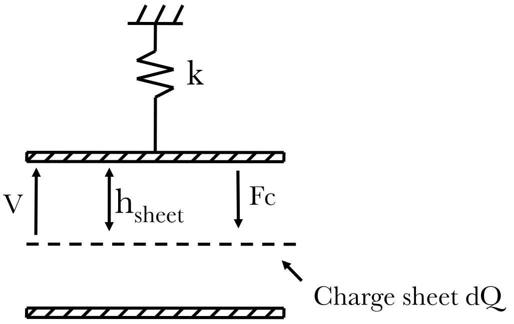

Figure 4 – A parallel plate actuator, with an infinitely thin charge sheet between the two plates. The top plate can move down towards the bottom fixed plate through elongation of the spring k.

This can be studied by inserting a charge sheet in the gap of a parallel plate electrostatic actuator like the one described in Figure 4, then there is an attractive force generate by this sheet, that will tend to close the gap between the two plates.

When the total amount of charges is large enough to overcome the spring restoring force, then the two plates can remain stuck together as long as the charges remain in place.

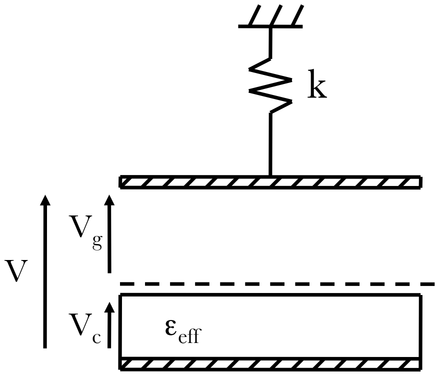

Figure 5 – Voltage distribution over a parallel plate electrostatic actuator. V_c is the voltage induced by the charge sheet, and Vg is the voltage across the electrostatic gap. V, the applied voltage is the sum of the two

If there is a discontinuity in the gap, like the dielectric / air interface shown above, electrical charges can accumulate at the interface, especially when the dielectric has a very small leakage current.

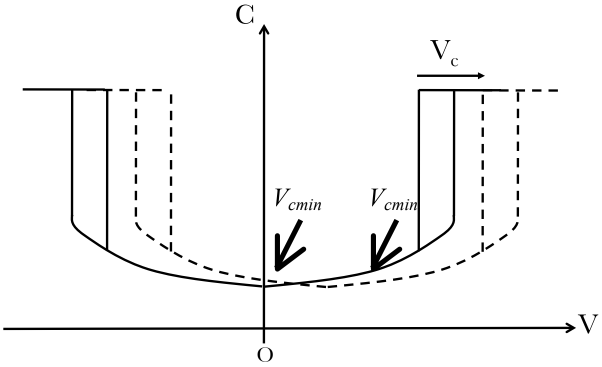

Figure 6 – Effects of the charge sheet in Fig. 2 on the capacitance to voltage characteristics of the switch

The accumulation of charges is the time integral current, and the time to failure can be predicted by measuring the current in the switch. Therefore, in such an ideal case, the lifetime of the switch can be computed by measuring and modeling electrical currents inside its dielectric layers. Since these current laws are very well known, they would also permit to determine the lifetime of the devices versus time, applied bias waveforms and also temperature. This ideal approach is outlined below.

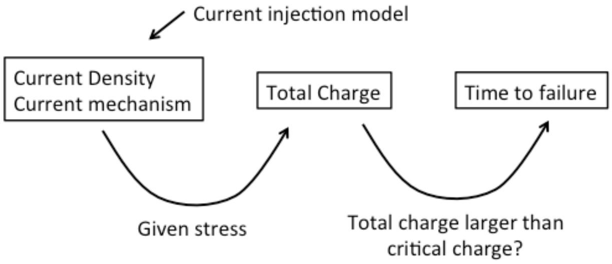

Figure 7 – Modeling for time to failure analysis, for ideal charging mechanism

However, and unfortunately, charge retention is not the only mechanism that may affect the C (V) characteristic of an electrostatic actuator, and there are mechanical factors at play as well. Possible evolutions of C (V) characteristics are described below:

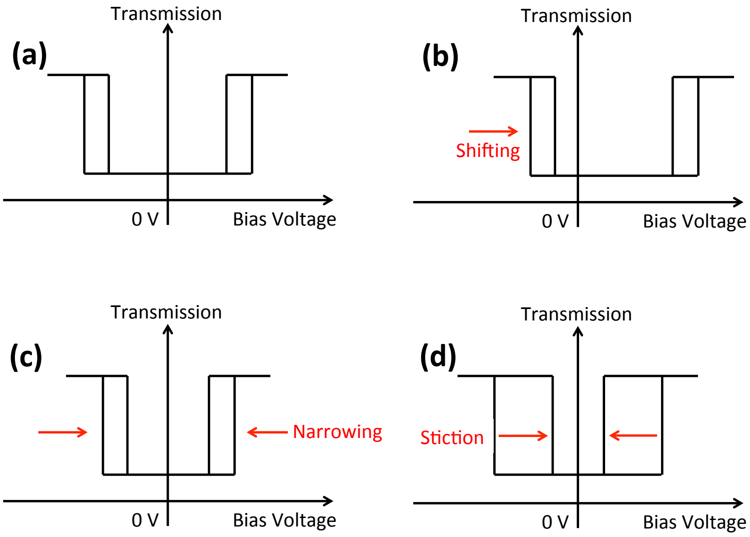

Figure 8 – Electrostatic actuator evolutions. (a) Initial state. (b) 'Ideal' charging. (c) Narrowing. Can be mechanical creep, or distributed charging. (d) Stiction. Can be mechanical wear, residues, charging and contact contamination. Both b, c and d can lead to permanent failure of the actuator.

The **case (a)** is a typical recording of the C(V) recording of an electrostatic actuator without charges stored inside the dielectric layer.

(b) is the effect that a stored electric charge has on the C(V) characteristics. In this ideal case, the time to failure can be predicted by using the models described in the following paragraphs of this report.

The **case (c)** is more complicated, and the origins of this effect are more speculative. On one side, distributed charging, as described by Rottenberg et al, can explain this evolution of the C(V) characteristics. Also, mechanical creep can readily explain this evolution, since this phenomenon reduces the effective stiffness of MEMS mechanical structures and reduces both the pull-in and pull-out voltage. Recently, several groups have shown that hard metals, single crystal mechanical structures permit dramatic reduction of these effects. It is also worth noting that the distributed charging model was taken after measurements on Aluminum-based RF-MEMS, which is a material well known for being subject to mechanical creep.

The last **case (d),** is typical of Ohmic MEMS switches, where the actuator is relatively stable but the contact tends to become sticky, and reduces the release voltage.

All these mechanisms, charging, creep, stiction, combine themselves in real components, and it is very difficult to separate one effect from the other. The minimum capacitance voltage (V_{cmin}), is therefore very helpful for charging only observation and is very often the only way to observe charging in real life MEMS switches.

2) Concepts to reduce dielectric charging

The initial proposal for reduction of avoidance of dielectric charging was centered on reducing the electric field in the electrostatic actuator, by using air gaps inside the switch. This technique has been covered using know-how of the laboratory and the fabrication of air-gap inside structures, and design structures with moderate (10-20V) actuation voltages.

3) Test vehicles

The test vehicles were MEMS switches as basic as possible. The devices were made using electroplated metal beams, which were stopped on a thin dielectric layer. The second test vehicles were using decoupled actuation, with air gap and no direct contact between actuation electrodes and the beams.

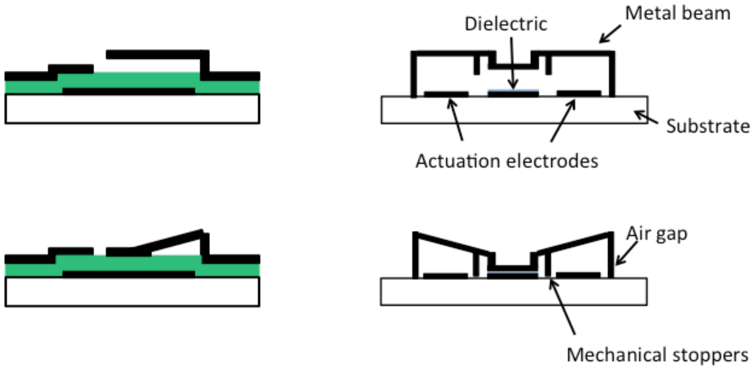

Figure 9 - First versus second test vehicles

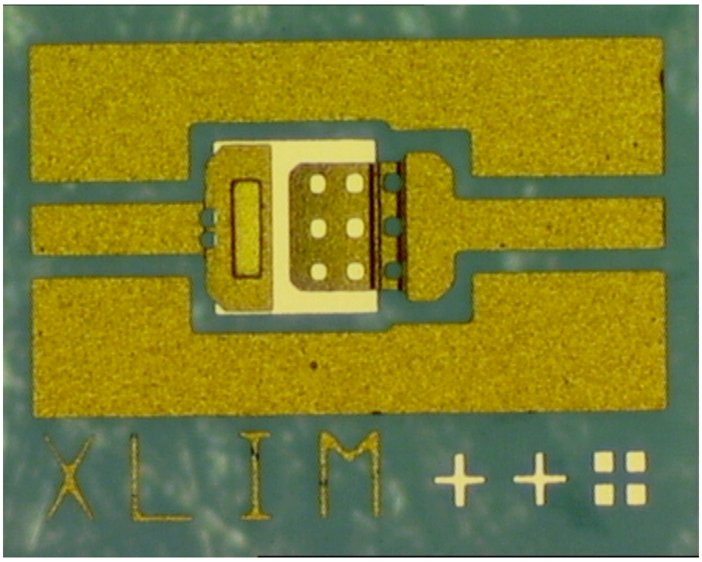

Figure 10 - Microphotograph of the Al2O3 based switch

A cross section of the device is shown on Figure 11, in the up and down states.

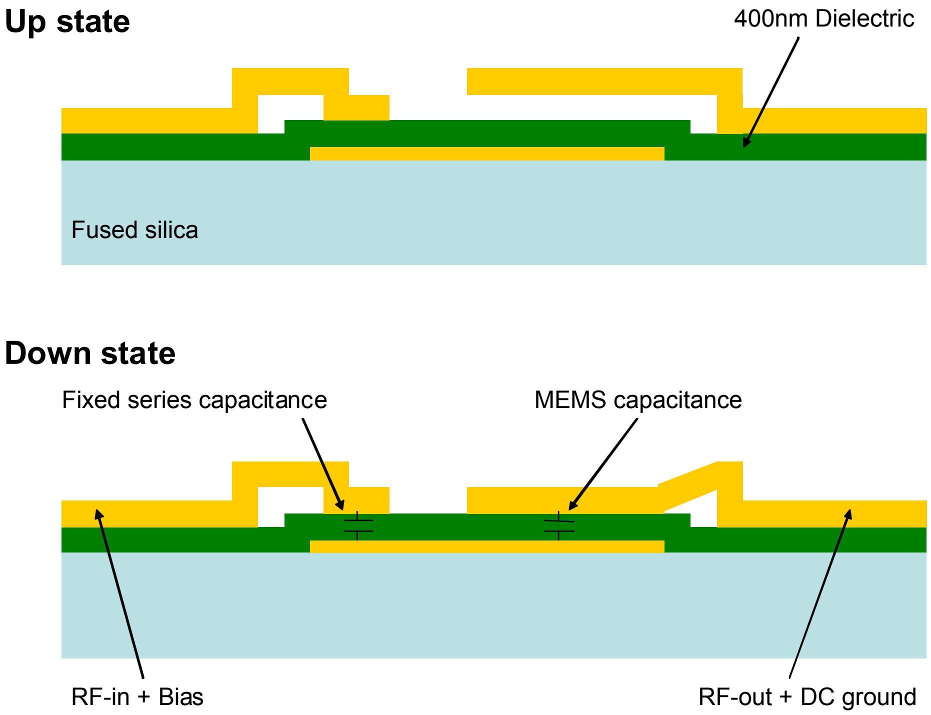

Figure 11 - Cross Section of the TV11 and TV12

Typical measured capacitance to voltage curves are shown below.

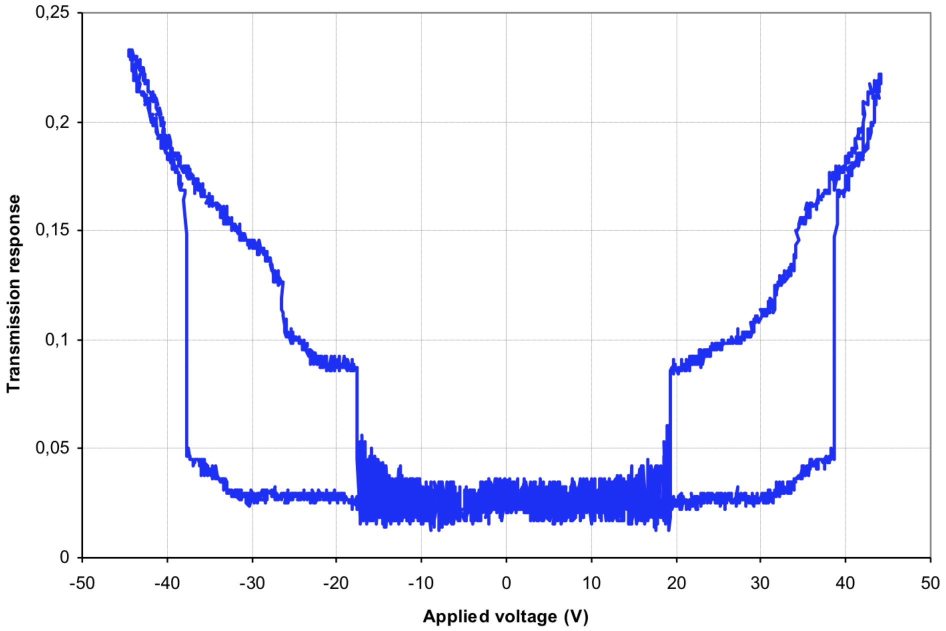

Figure 12 - Typical recorded Response of the test bench presented above

In the present example, the pull-in voltage is 38 Volts, and the pull-out voltage is 18 volts. The curve should be exactly symmetrical with respect to the voltage origin, but we found that there is always a small shift on the positive pull-in voltages and pull-out voltages. After many discussions with colleagues in LAAS CNRS, and in Thales Alenia Space, we found that this small shift is always present, even on different benches. Interestingly, it is also present when measuring commercial devices on our test bench, but also on simpler versions, combining a simple oscilloscope and a high voltage source. So far, we have no sure explanation for this phenomenon, but we attributed this shift to the test bench.

These basic devices were indeed quite good at trapping charges, and we have used bias waveforms with low duty cycle (25%) in order to achieve lifetimes that are compatible with test times.

We have seen that charging sequence results in a relatively modest shift in the pull in voltage, but permanent hold down of the device results in rapid failure of the device.

We have tested two dielectrics on these switches, SiN and AlN, and they gave different results but both were not able to bring RF-MEMS reliability to a correct order of magnitude. **The devices were failing quickly if a permanent actuation bias was applied**.

4) Second test vehicle fabrication

The RF-MEMS switch TV cross section is shown in Figure 13. The device is using two different air gaps, and two different actuation zones. The actuation part is using an air gap, on the outer part of the suspended metal beam. In the down state, the center part comes in contact with the electrode covered with dielectric. In the down state, the actuation part of the metal membrane is always separated from the actuation electrode by an air gap, and the electric field is low enough to obtain very small charge retention.

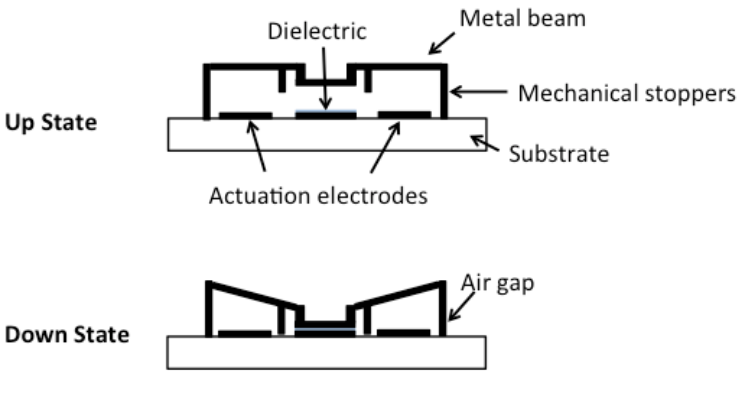

Figure 13 - Cross section of the proposed TVs

In the down state, the center part of the switch in contact with the bottom electrode sees no electric field. It is possible to apply a small voltage with input-output biasing on this system, but the device can work without any bias.

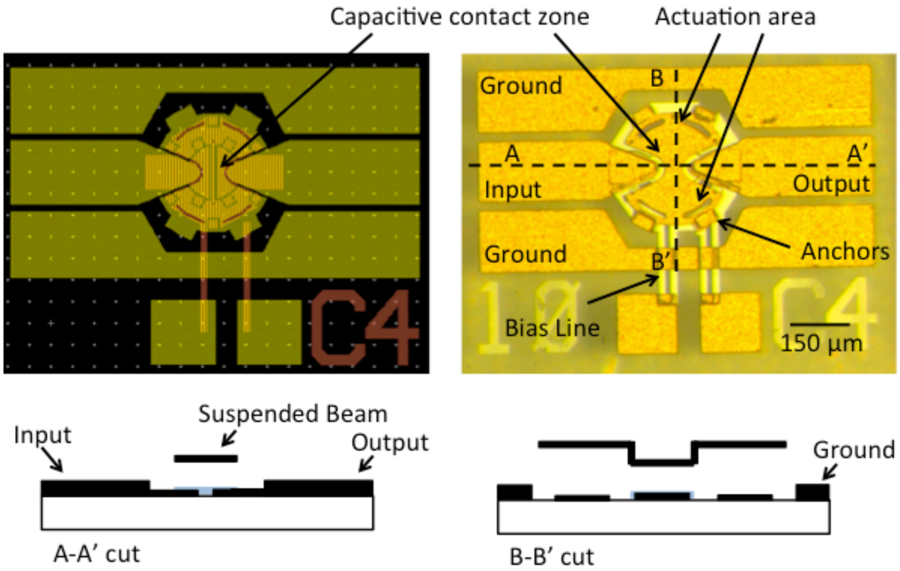

Figure 14 - Layout and microphotograph of a series implementation of the capacitive switch, with a cut along the propagation axis (A-A') and across the propagation axis (B-B')

The equivalent scheme is a simple capacitance in series on a 50 Ohms transmission line. The voltage to capacitance can be easily read using the transmission parameters on a probe station.

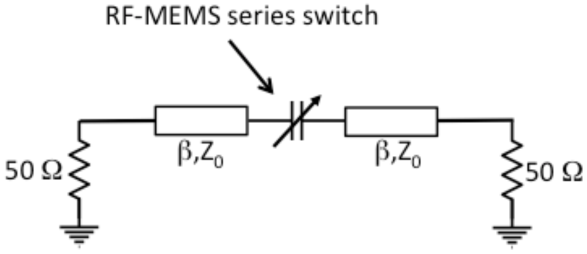

Figure 15 - Equivalent scheme of the switched capacitor

A specific TV (Thin AlN) has been circulated among the partners.

The measured pull-down voltages are between 40 and 50 Volts, with small dispersion between one type of sample and another RF testings have been also conducted at Thales Alenia Space in Toulouse on 15 samples, in order to validate the measurements taken at XLIM.

The conditions are identical, and the applied bias voltage is 50Volts and the devices exhibited an on to off ratio between 4 and 5, in reasonable agreement with values measured at XLIM.

5) C(V) testing

The test benches are available both at the XLIM and Thales Alenia Space. Most of the tests were done on these benches.

a) Results at XLIM

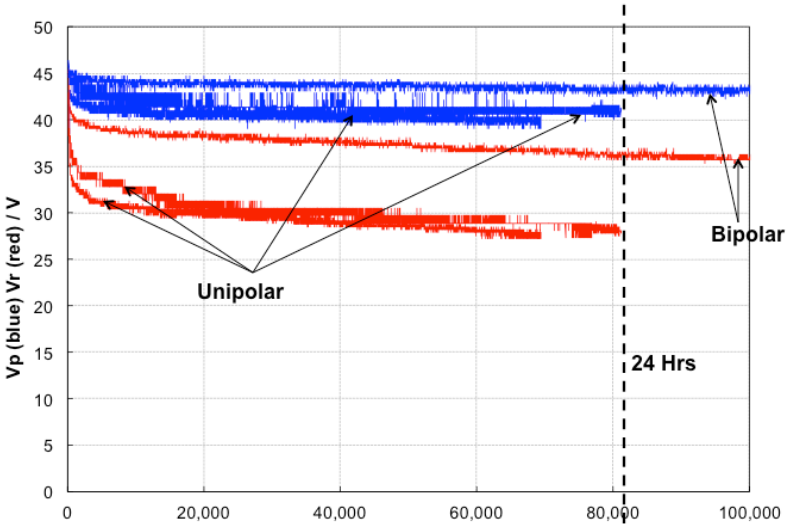

Figure 16 – Test results on 3 devices using unipolar and bipolar waveforms

The main results show that there is a very small difference between bipolar bias waveforms and unipolar bias waveforms, indicating that the measured pull-in and pull-out variations are not due to charge retention.

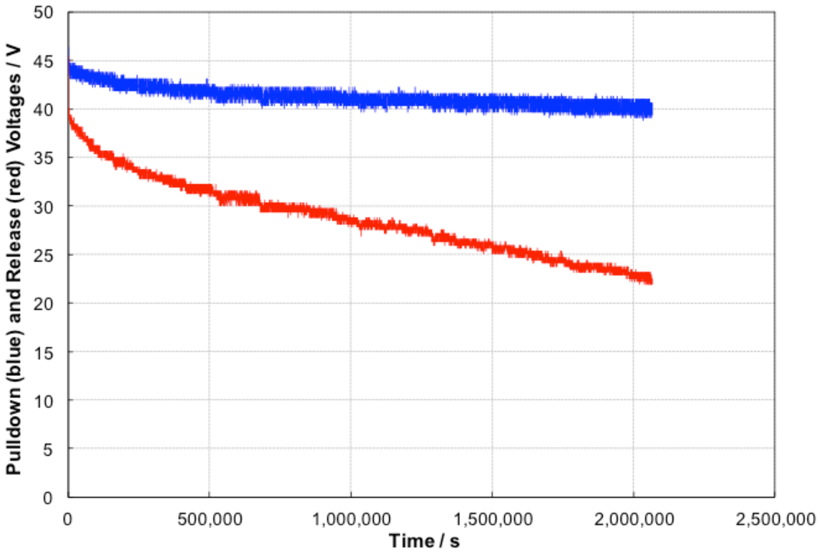

Figure 17 - Measured pull-in and pull-down evolution of the switch left in the down state for 3 weeks

Measurements taken for long periods (3 weeks) show that the device can be maintained in the down state without failure. The device still has some observable drift, but this was attributed to creep and center contact stiction.

b) Results at Thales Alenia Space

Three samples have been measured and tested at Thales Alenia Space. The applied stresses consist in holding the devices in the down state for several hours, and recording the scattering parameters before and after the application of the biasing stress have been applied.

This allows for both recording the switch capacitance characteristics and the pull-in and pull-out voltages on the switch. The test set-up in Thales uses a calibrated Vector Network Analyser for Transmission to Voltage recording and therefore permits to record accurate values for loss and isolation of switches.

The test set-up at Thales Alenia Space is shown below:

Figure 18 - Photograph of the test set-up at Thales Alenia Space

2 samples were subjected to 1 hour tests and 1 sample on a 15 hours test.

One can see that the up state capacitance is slightly increasing (increasing transmission), and that the down state capacitance is also increasing.

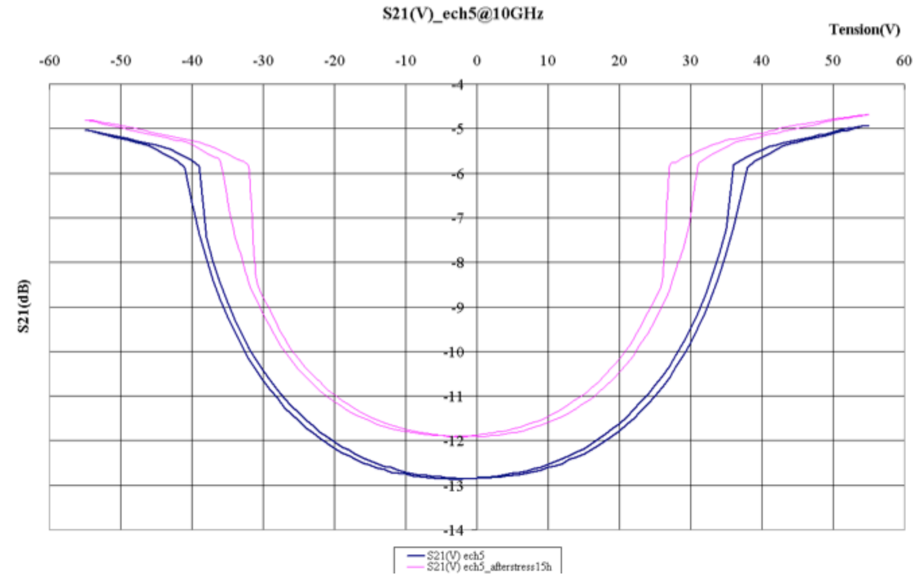

Figure 19 - Transmission vs Voltage characteristics before and after 15 hours stress

The difference between the minimal capacitance before and after testing has been attributed to mechanical creep, since there is no drift in the minimal capacitance voltage versus time. These devices have therefore no observable charging, as expected from the presence of an air gap in the actuator. The accuracy of the transmission to voltage measurements in Thales Alenia Space have permitted to clearly show mechanical creep in the structures.

6) In situ charge injection testing

The idea is to actuate the switch by the sides, in a similar manner as it was done previously, and then adding a bias voltage at the center electrode.

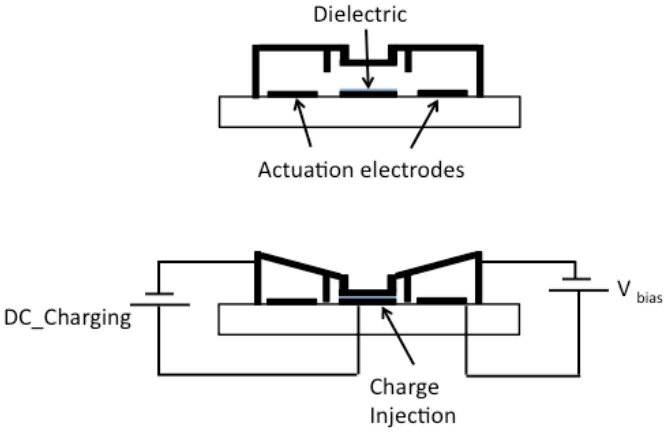

Figure 20 - Proposed scheme for measuring the amount of charges injected from the top actuator of the RF-MEMS device

By doing so, charges are injected on the top of the layer, with different bias voltage. There is an influence on the static behavior of the electrostatic actuator, and by observing this influence, we can see the decay of the injected charges versus time.

This is very similar to the AFM (Atomic Force Microscope) decay method, since charges are injected from the top electrode of the switch and the generated force can be next be detected from the change in the release voltages of the switch.

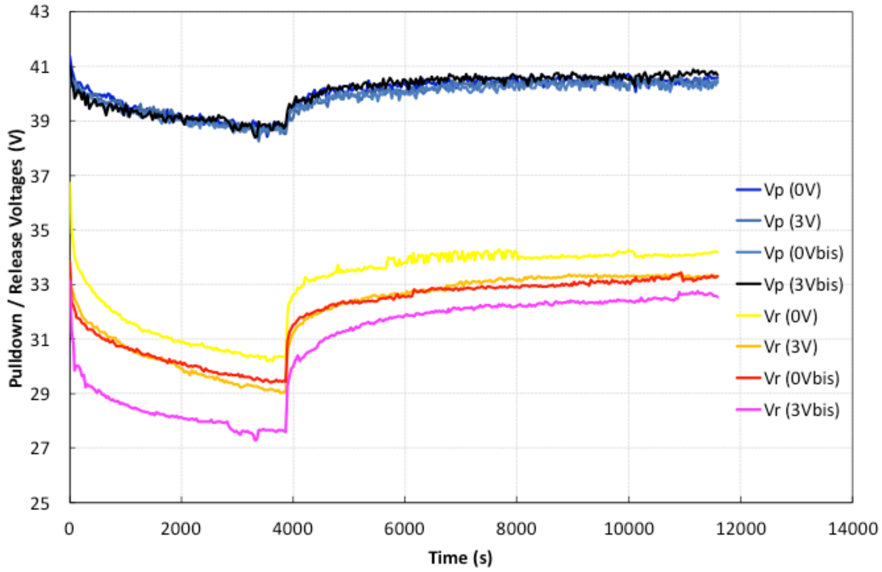

Figure 21 – Records of the pull-in and pull-out voltages on the switch, for successive tests with 0Volts and 3 Volts. The test was repeated twice.

These results are interesting but also indicate that there may be cumulative effects in dielectric / metal contacts. Among possible causes is metal wear, that would improve the metal to dielectric contact quality and adhesion properties.

This area clearly needs more investigation, but experiments are extremely time consuming, since the rest periods for the switches have to be a lot longer than stress time.

7) A quick look at commercial components

In the time frame of this project, several vendors proposed advanced products for cell phone tuning and MEMS relays for instrumentation. They also followed different approaches to both mitigate charging in dielectric layers and creep in mechanical structures. There are only a very few RF-MEMS devices that are actually on the market today (i.e. one can buy them). The devices are gathered in the table below. Ohmic switches are not using any dielectric layer in the electrostatic actuator and therefore present little or no charging. It is interesting to note that no drift could be measured on the Omron SMES type devices.

Vendor	Type of Switch	Mechanical Structure	Solution for Charging	Comments
Omron	Ohmic	Single Cristal Silicon	Air gap. No dielectric	No meas. drift of Vp @70°C, 62 Hours
Radant	Ohmic	Hardened electroplated gold	Air gap. No dielectric	Meas. 3 Volts drift @ 70°C, 75 minutes
Wispry	Capacitive	Silicon Nitride	Air gap + Dielectric	Not tested
Cavendish Kinetics	Capacitive	Aluminum alloy	Air gap + Dielectric	Not tested

Tableau 1 - Comparison of the different commercially available devices.

8) Conclusions

The results presented in this report, and that have been collected during this project are showing the main points:

- **<u>Charge trapping</u>** is clearly a large issue on RF-MEMS. The first generation of MEMS switches shown at the beginning of this project had lifetime that was measured in minutes. The second generation of components has lifetime that can be measured in months. In this project, we have shown that the second generation of devices can be left in the down state for several weeks. **<u>The solution for this</u>** is to separate the actuation electrodes from the RF electrodes. This would work for ohmic and capacitive switches.
- The currents inside dielectric layers can be accurately modeled, and can predict charge injection induced stiction of electrostatic actuators.
- Relatively simple approaches works: air gap actuators, that prevent any contact between MEMS beams and dielectric layers in the components dramatically reduces charging. Lifetimes are improved by several orders of magnitude, with little dependence of the nature of the dielectric layers that are being used. To the best of the knowledge available to us, **<u>this approach is successfully followed by all RF-MEMS vendors.</u>**

- Still, the contact between a metal beam and a dielectric layer involves wear and irreversible evolution, as observed at the end of the project. This aspect needs further investigation.
- Air gaps are subject to break down, and permanent failure in open laboratory ambient. Packaging in an inert gas or vacuum is needed. This failure mode is particularly harmful, since this is very difficult to predict and happens in a random fashion. This point has been problematic for repeating tests at Thales Alenia Space and XLIM. The vacuum measurement chamber at XLIM reduces breakdown while open laboratory tests in Toulouse have been difficult especially when sharp transient bias voltages were applied on switches.
- Ironically, things become particularly complicated as soon as one can reduce the influence of charging. At the end of the project, we had an extremely hard time to separate observations that have a mechanical origin from the ones that are due to charge trapping. Mechanical creep in electroplated structures has a strong effect on the reliability of MEMS structure and this particular point needs to be further studied in close detail.

The recommendations for future works are as follows:

- Use high quality, thin dielectric films.
- Develop good, low cost **hermetic packages** for RF-MEMS. A controlled atmosphere is needed to mitigate breakdown failure of switches, independent of protecting devices from contact pollution and other effects.
- Use hard metals, high temperature dielectrics, or single crystals for mechanical structures, in order to put mechanical creep out of the equation.
- De-correlate actuation from capacitance to voltage characteristics. Use separate electrostatic actuation for capacitive switches and Ohmic switch.