Reliability of RF-MEMS

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***Abstract* — The continuously evolving MEMS technology for RF/microwave applications poses issues regarding new reliability and lifetime estimation. We will overview the most important degradation mechanisms concerning capacitive and ohmic RF-MEMS devices and their effects on the device lifetime. Preliminary results will also be given on ElectroStatic Discharge effects on ohmic shunt switches adopting a Transmission Line Pulse stress technique.**

I. Introduction

MicroElectroMechanical Systems (MEMS) devices for radio-frequency and microwave applications, already acclaimed in the past decade as one of the most promising emerging technologies, have recently received further attention for their ability to implement reconfigurable passive networks for future generation multiple-standards and multiple-frequency wireless terminals [1]. In particular, the focus is on a class of devices including both varactors and capacitive or ohmic contact based switches and multiplexers, all functioning at RF-microwave frequencies. These devices have potential performances that can surpass the limits of their current equivalent implementations using more traditional solid-state technologies. They maintain good miniaturization and can be integrated with solid state circuits, either above IC or in the same package. They exhibit almost zero power consumption; extremely good linearity, both in terms of IIP2 and IIP3 (both > 70dBm); very low losses (high Q), making them very suitable for tuning. Finally but most importantly, RF-MEMS switches achieve very low insertion loss (<0.1 dB up to 100 GHz) while maintaining high isolation (>20 dB). From the technology standpoint, they tend to require low-cost fabrication processes compared to RF and microwave solid-state integrated circuits.

All this notwithstanding, all the above and further benefits go along with a series of shortcomings, mostly related to the poor maturity of still evolving design methodologies and fabrication processes. The paradigm shift that these new technologies have introduced is also accompanied by lack of standardization in the fabrication process, with a big impact on the design flow, limited reliability data compared to microelectronics standards, and poor knowledge of ageing mechanisms and reliable design practices.

Nonetheless, in the last year or so, a number of academic and government laboratories and companies have started to report cycling lifetimes for fabricated prototypes that are in line with requirements from both military and commercial potential users. Over 100 billion cycles for ohmic contact switches have been reported, by technologies such as Radant MEMS [2], MIT Lincoln Labs or Raytheon. As a result, some commercial products are starting to appear in the market, mostly linked to government institutions so far.

In terms of future applicability of these technologies to higher-volumes, lower cost-per-unit applications, such as the wireless market, there is still a lot to be seen. Conventional solutions are currently reaching levels of cost reductions through batch processing that could hardly be tackled by emerging technologies. The RF-MEMS technology does not only need to prove as performing and reliable as its established competitors, but it must provide for completely new functionalities and unexplored circuits and systems solutions, to gradually find its way into the commercial RF-microwave market.

In the present paper we will discuss some key mechanisms affecting RF-MEMS reliability, expecially focusing on capacitive and ohmic switches, their degradation behavior due to cycling and the effect of ElectroStatic Discharge on the device lifetime.

II. RF-MEMS Reliability Classes

Despite of its original definition, the MEMS classification has now became an all-embracing one that tends to include any device that is fabricated with at least one micro-machining technology step. For this reason, it is necessary to try to classify all different RF-MEMS devices nowadays under development, in a way that is meaningful for reliability studies, in order to identify some common criteria for the formulation of ageing models and accelerated tests criteria.

Table I summarizes three different classes that can be defined for RF-MEMS devices, according to the level of mechanical complexity and boundary conditions [3]. Class I comprises all passive lumped or distributed components that have been designed for diminished losses through micro-machining fabrication. No mechanical movement of any part of the geometry is necessary during functioning, although some deformations might occur as part of the fabrication process, such as in self-assembled out-of-plane structures. Long-term stability and reliability issues of such devices do not differ substantially from those of traditional passive components. Electromigration and thermal burnout effects are typical mechanisms occurring to metallisations. Special structural stability issues might occur to thin dielectric membranes, often utilized for high-Q passives fabricated through backside bulk micromachining. Membranes also tend to exhibit thermal issues related to poor heat diffusion to the bulk material.

Class	Micromachined Structures	Movable Parts	Impact	Examples
I	**YES**	NO	NO	High-Q Suspended Inductors: spiral, self-assembled coils; Low-loss RF Membranes; RF-CMOS Substrate Removal Post-Processing
II	**YES**	**YES**	NO	Very high-Q microelectromechanical resonators; continuously tuning capacitors
III	**YES**	**YES**	**YES**	Ohmic contact RF-MEMS relays; switched capacitors; capacitive coupling RF-MEMS switches and multiplexers.

TABLE I
SUMMARY OF CLASSES OF RF-MEMS DEVICES [2]

Moreover, devices that undergo temperature cycles during assembly and packaging can experience unrecoverable structural deformations leading to device failure.

The second class of devices require some mechanical movement during functioning, either small-signal mechanical vibrations or large-signal displacements relative to the substrate reference. Examples from this class of devices are very high-Q micro-electro-mechanical resonators or continuously tuning capacitors. Cycled mechanical deformations and steady-state vibrations introduce new stress mechanisms on the structural parts of these devices. Mechanical relaxation of residual material stress, plastic deformations under large-signal regime, creep formations and fatigue can all impair the stability of electro-mechanical device behavior and eventually cause device mechanical failure. Finally, other surface effects such as oxidation or absorption can also result in changes of effective mass or stress of a moving or vibrating structure, causing stability issues and device failures.

Finally the third RF-MEMS class includes all devices that require two normally separated mechanical parts to reach and maintain contact during a certain fraction of the operation cycle. The presence of mechanical contact introduces a whole new class of reliability issues, related to both mechanical and electrical phenomena. Probably the most important effects impairing device functionality is the 'stiction' of the mechanical parts that reached contact, which is the inability to restore a resting position after the actuation stimulus has been removed. Several causes can be the origin of stiction: capillary effects due to changed environment conditions; electrostatic charge accumulation or redistribution within dielectric layers; micro-welding of metals due to DC or RF power. Electrical ohmic contacts occurring between two metallic surfaces can also suffer from stability problems due to cycling, resulting in changes in ohmic contact resistance. The causes can be diverse, such as surface contaminations, material transfer and erosion, surface changes due to absorption or oxidation.

This yet non-exhaustive collection of possible reliability and failure mechanisms occurring in RF-MEMS devices is depicting a very complex scenario for the lifetime testing of these devices, asking for the definition of new methodologies, device degradation models and accelerated tests criteria, all covering diverse and cross-coupled physical domains.

II. OPTICAL DIAGNOSIS TOOLS FOR MICROSYSTEMS

A key diagnosis tool has been developed by some metrology research laboratories in the past few years, following the increasing requests from the microsystems research community. The system is based on optical surface profilometry and it allows for contact-less inspection of the device 3-dimensional profile without any physical contact, therefore in a fully non-invasive way. The principle is based on optical interferometry, either white-light or phase-coherent, following the principles described in [4].

Through this technique, different investigations can be performed, on the height distribution of the device, on curvature and tilt of mechanical parts, on the surface roughness of finished materials. Furthermore, the relatively high speed of acquisition allows for a dynamic mode of operation, after adding a stroboscopic illumination control. RF-MEMS devices can be inspected during their electro-mechanical functioning, reconstructing the deformation of the whole structure during a complete cycle through phase at a given frequency, or by extracting the complete frequency dependent behavior description in terms of resonant frequency modes and quality factors.

III. PROCESS RELATED ISSUES

Malfunctioning of an RF-MEMS device can appear straight after fabrication or after a relatively short life time, and is typically related to process related issues. Two classes of problems can be identified, one mechanical and one electrostatic. The presence of residual stress within the structural material of the device, or worse stress gradients, if not taken into account within the models during design, can lead to permanent deformations of the released structures, resulting in poor performances or even device failure. Non-invasive inspection techniques such as optical interferometry can be the quick and easy tool to identify these problems and even try to extract the amount of stress causing the deformations.

A second electrostatic fabrication issue affects typically the dielectric layers used as isolation in capacitive switches, and is related to charge accumulation during process steps. The immediate consequence of this is a shift in actuation voltage from the original design, leading possibly to device failing to comply to electromechanical specifications. Effects of charge accumulation within the dielectric layer will be further discussed in the next paragraph.

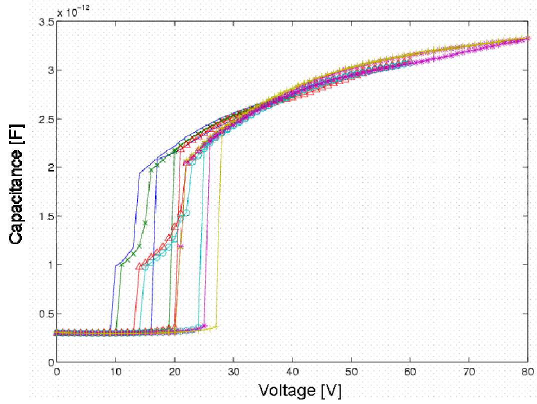

Fig. 1. Capacitive switch showing pullin and pullout voltage walkout due to charge accumulation within the dielectric layer.

IV. Electrostatic Actuation Related Issues

Dielectric materials are potentially prone to the accumulation of fixed or slowly movable charge, related to various physical mechanisms such as the presence of crystalline defects, surface contamination or polarization. If we consider the classical electrostatic actuator model, any charge distribution within the isolation layer will result in a shift in effective electrostatic force at a given applied voltage. Two different effects have been reported in literature, depending on the presence of net charge accumulation within the dielectric.

The simple case is when a significant net charge Q is accumulated within the dielectric layer, either from process steps during fabrication or during lifetime cycling due to applied voltages. In this case one can observe a shift in the d-V and C-V curves, equivalent to the Q/C_{down} effective voltage [5]. Both the pull-in and the pull-out voltages will be affected in the same way, leading possibly to the device failing to actuate at a wanted voltage, or to electrostatic stiction. Figure 1 shows an example of pull-in and pull-out voltages walkout in a switched MEMS capacitance.

The second possibility is to have a non-uniform charge distribution across the device geometry, while maintaining a zero net charge within the dielectric. Rottenberg gave an account of how the charge variance can be responsible of failure due to disappearance of the pull-out bias, with electrostatic stiction appearing with hardly any shift in pull-in voltage [6]. A further increase in charge variance can also lead to disappearance of the pull-in bias, leading to permanent device self-actuation regardless of the actuation controlling voltage. Non-uniform charge distribution can result from processing issues, but also from non-uniform field distribution during the device actuation, due to the deformation of the actuated membrane and to the residual air-gaps typically present in the down-state position.

V. Metallic Contact Reliability

The stability and reliability of direct metal-metal ohmic contacts during operation can be hampered by several degrading mechanisms, such as microwelding, electro-migration, metal softening, erosion and material transfer, surface contaminations. Both the number of cycles and the total time the switch spends in the actuated state are critical for these degrading mechanisms. Hot and cold switching requirements are also key factors in defining the life time of the ohmic contact.

Figure 2 shows examples of the evolution of the isolation parameter of an ohmic shunt switch stressed by pulses of different width with a period of 1ms. All examined devices exhibit a decrease in performances after a thousand cycles, accompanied by a heavy degrade of the S_{21} parameter after 1 million of cycles. The device stressed with 25% duty cycle fails to actuate several times already after some thousand cycles, but never fails completely. On the other hand, the device stressed with a duty cycle value of 75% fails after just 20000 cycles.

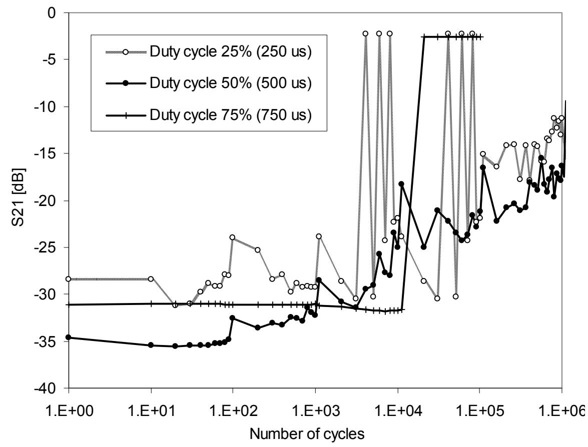

Fig. 2. Degradation of the isolation parameter (small signal S_{21}) during different duty cycle stresses.

VI. Electrostatic Discharge Testing

The ESD sensitivity of MEMS, despite of the very poor investigation carried out up to now, is a real issue and usually only 100 V of HBM test is sufficient to produce failure [7]. We have tested RF-MEMS by means of a Transmission Line Pulse (TLP) technique that is a widely used testing method that allows not only a device standard characterization, but also a detailed investigation of the device in EOS/ESD regime [8]. The TLP tester is capable of providing rectangular pulses with duration ranging from 1ns to 1µs with a sub-nanosecond rise time and variable amplitude up to several kV (and/or several Amps). The TLP adopted in this study works on the constant impedance Time Domain Reflectometer (TDR) methods [8] for wafer level testing. We have submitted to TLP stress the ohmic RF-MEMS switches applying the TLP voltage between the actuation pad and the RF-ground. The actuation structure can be modeled as a capacitor so, as depicted in Fig.3 at low applied voltages (V_{DUT}), the I-V plot is similar to an open circuit. When the applied voltage reaches around 230 V, the device

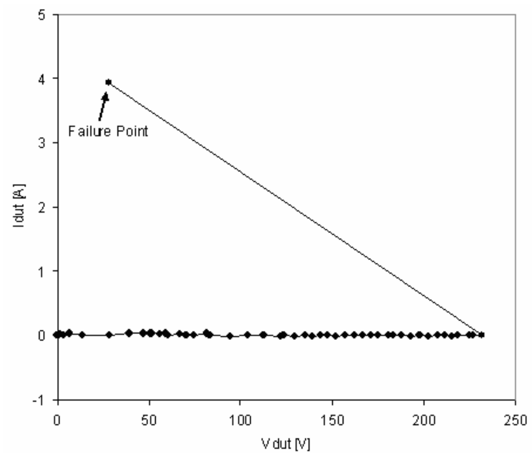

Fig. 3. I-V trace of the succession of TLP stress pulses.

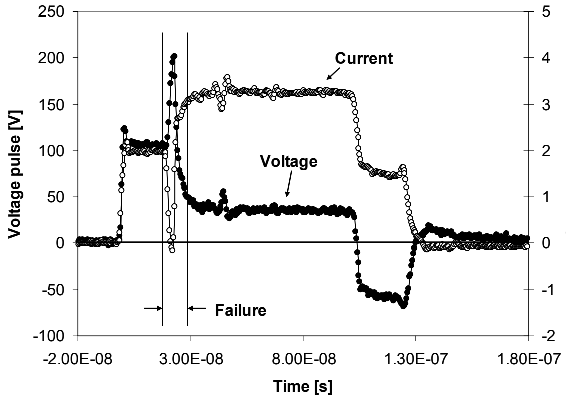

Fig. 4. Current and voltage waveforms of the TLP stress pulses, showing the device damage window.

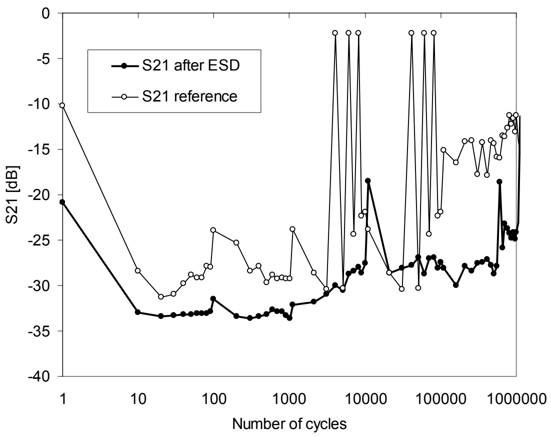

Fig. 5. Isolation parameter degradation of ohmic shunt switches, comparing an ESD stressed with a reference untreated device.

does not behave anymore as an open circuit, and a large current is measured through its terminals.

This behavior can be due to both an electrostatic actuation and/or an in-air discharge (arch discharge) due to the high potential applied to the electrodes. The voltage and the current waveform pulses during the TLP test at the failure point of Fig. 3 is shown in Fig. 4. In the highlighted "Damage" region clearly a current increase and voltage decrease is observed due to the transition from an open-circuit to an almost "short" circuit regime. After the TLP stress 1 million cycles were applied and monitored to the RFMEMS in order to study the effect of the TLP stresses. Figure 5 shows the transmission scattering parameter before and after the TLP stress, exhibiting a noticeable increase (improvement) in the switch isolation. For some unknown reason, the device submitted to the TLP stress (Fig.3) presents a lower degradation (lower decrease of the insertion loss parameter) than the untreated switch.

VI. Conclusion

An account was given of the complex mechanisms defining reliability of novel RF-microwave devices based on Micromachining technology (RF-MEMS). Charge distribution within dielectric layers and ohmic contact stability issues were identified as two main concerns for the lifetime durability of capacitive and ohmic RF-MEMS switch devices. Preliminary results are also presented of ElectroStatic Discharge stress on ohmic shunt switches, utilizing a Transmission Line Pulse technique.

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