RADIATION SENSITIVITY OF OHMIC RF-MEMS SWITCHES FOR SPATIAL APPLICATIONS

A. Tazzoli, G. Cellere, E. Autizi, V. Peretti, A. Paccagnella, and G. Meneghesso
Department of Information Engineering, University of Padova, Italy

ABSTRACT

The impact of 2MeV protons and 10keV x-rays radiation stresses on electrostatically actuated ohmic RF-MEMS switches has been analyzed at increasing radiation dose and during subsequent annealing at room temperature. Small variations of electrical parameters (actuation and release voltages) have been identified, accompanied by a strong rf-performances degradation. Monte Carlo TRIM simulations have been carried out to understand the mechanisms responsible of such degradations, finding that both NIEL and ionizing damages appear to play an important role.

INTRODUCTION

Radio Frequency Micro-Electro-Mechanical Systems (RF-MEMS) have been proved to be interesting candidates to overcome the limits of actual state-of-art solid state devices. Good rf performances, optimum linearity, low power consumption, and low cost production are just some peculiarities of RF-MEMS switches very useful for today wired and wireless terrestrial applications [1]. Furthermore, small dimensions and light weight make such devices very appealing for spatial applications. Despite these positive aspects, all the above and further benefits go along with a series of present-day shortcomings; these shortcomings are mostly related to the maturity of today's still-evolving design methodologies, lack of fabrication processes standardization, limited reliability database, and poor knowledge of ageing mechanisms and reliable design practices. These limits are even more important for the performance-hungry but reliability-critical satellite applications, since in the harsh space environment radiation induced damage is one of the main causes of failure [2]. In particular, the behavior after exposure to ionizing radiation of devices having mechanical motion governed by electric fields across insulators has been seldom studied, mainly in MEMS sensors [3] or capacitor-like structures [4]. Just few authors have analyzed complete RF-MEMS devices [5], [6].

This paper begins to fill the gap, presenting results on the reliability of ohmic RF-MEMS switches irradiated with 2MeV protons (AN2000 accelerator at INFN, Legnaro, Italy), and 10keV x-rays (INFN, Legnaro, Italy).

RADIATION STRESS

It is well known that space can be a harsh environment for traditional solid state devices. Ionizing radiation comes in form of protons or ions trapped in the van Allen belts, of solar wind (with its periodical variations), and of protons and ions of galactic origin [7]. Since several years, radiation and EOS/ESD phenomena have been addressed as the main causes of mission failure, as reported by Koons et al. [2]. Most works were carried out considering traditional solid state electronic components, but recent studies have indicated the possibility that also micro-mechanical structures can be hampered by radiation damages. The standard satellite radiation shielding has been proved to be a good solution to guarantee the electrical device lifetime during space missions, however, since the potential killer application of RF-MEMS devices would be on nano-satellites, the efficiency of such a protection on small and light satellites is yet to be verified. Further, even if a relatively thick shielding helps reducing the electrostatic charging and the total dose delivered to the electronic devices, it cannot totally suppress it.

The effects of ionizing radiation on microelectronic devices can be broadly divided into three categories. **Single Event Effects** are the macroscopic manifestation of single ions, such as the bit flip in a SRAM. To date, this should not be a problem with MEMS. **Total Ionizing Dose** effects are the progressive buildup of defects, mainly in the dielectric layers, due to the energy loss via ionization. Electrically active defects can be of different kinds, including charge trapping (E' and P_b centers), Si/SiO_2 interface defects, and the generation of mobile charge [8]. These sort of effects need to be considered for RF-MEMS since charge trapping is universally recognized as one of the most impairing problems for the reliability of electrostatically actuated switches. Finally, even the most ionizing particles lead to a certain amount of **Non Ionizing Energy Loss** (NIEL), that is, an energy loss due to interactions with atomic nuclei and not to the direct generation of electron/hole pairs. These interactions typically result in the generation of point defects which can, for example, degrade the gain of bipolar transistors [9]. In the same way, NIEL can lead to a modification of the Young module of adopted materials, going to modify the mechanical properties of the MEMS structural parts, but also making the device more vulnerable to creeping and fracture.

DEVICE DESCRIPTION

Focus of this work are several typologies of ohmic RF-MEMS switches built by FBK-IRST (TN, Italy). Devices have been designed in both shunt (normally closed) and series (normally open) configurations, with two kind of suspension structures: meanders based, with a low spring constant (see Figure 1a), and with straight beams (see Figure 1b) with an higher spring constant leading to an higher restoring force. Another design variation regards the way in which the suspended membrane gets in touch with the bottom metal layer when actuated. The contact is achieved by the impact on dimples (see Figure 1c), or simply with flat surfaces. A detailed description of the switches design, adopting an interdigitated topology in order to reduce charge trapping phenomena can be found in [10].

The technology utilized for the fabrication of ohmic RF-MEMS switches uses a surface micromachining process based on electrodeposited suspended gold for the membrane layer (see the cross-section in Figure 1d).

978-1-4244-2978-3/09/$25.00 ©2009 IEEE

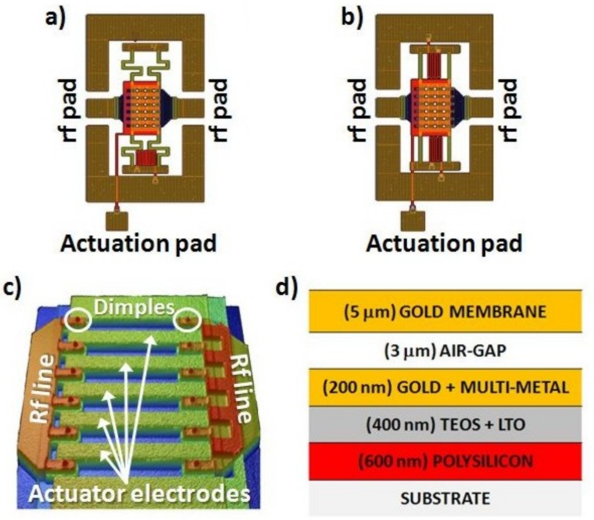

Figure 1: Tested devices layout: meanders based suspensions (a), and straight beam suspensions (b); optical profilometer image of a series switch (c) after suspended membrane removal; schematic process description (d).

The same gold layer is also available as low-loss RF signal path, whereas an high resistivity polysilicon layer is used for actuation electrodes, and a further Al-Ti-TiN multilayer for RF-signal underpasses. A thin evaporated gold layer is deposited over the signal underpass electrodes in order to achieve a gold-gold ohmic contact upon actuation. Direct contact is allowed only between the plate and the signal electrodes, by raising the signal underpass metal above the level of the poly electrodes, through the placement of poly dummy rectangular bricks. A 5μm thick electroplated gold layer is used for the plate to improve its rigidity, while a thinner (1.5μm) gold membrane implements the four suspending beam springs. Due to requirements for the release etch step, the suspended membrane is realized as a perforated plate structure with 20x20μm holes with 20μm separation. More details on the FBK-IRST process can be found in [11].

EXPERIMENTAL RESULTS

In this work we have submitted RF-MEMS switches to protons and x-rays radiation sources analyzing the impact of such a stress on the rf and electrical parameters of the devices with the increase of the radiation dose, and during the successive days of annealing. The setup adopted to characterize the switches is based on a Vector Network Analyzer (Agilent HP8753), for the measurement of the rf-performances, and a Source Meter (Keithley 2612) to bias the device and measuring the current drained by the actuator structure. The measurement starts from 0V up to $+V_{MAX}$, goes back to 0V, decreases down to $-V_{MAX}$, and finally comes back to 0V. This procedure leads to the traditional hysteresis-like diagram reported in Figure 2 (consider the “fresh device” curve), and it is possible to extract the actuation voltage ($|V_{ACT}|$) the release voltage ($|V_{REL}|$), and the S_{11} and S_{21} parameters. Furthermore, considering the graphs symmetry or translation, it is possible to study the presence of charge trapping or redistribution phenomena. More details on the adopted setups are reported in [12].

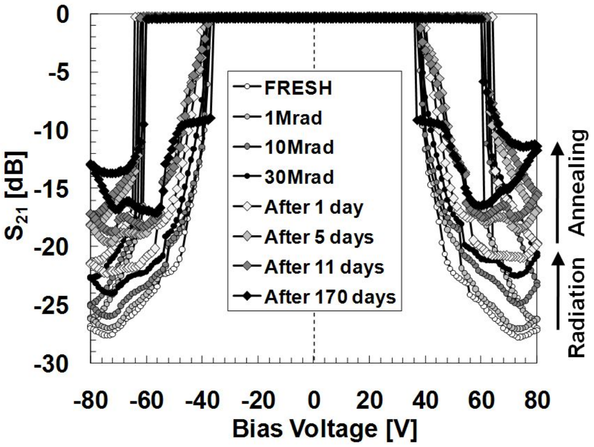

Figure 2: Degradation of S_{21} (V_{BIAS}) of a shunt switch (straight beams) during the protons radiation stress and the successive days of storage (test conditions: f_{rf} = 6GHz, P_{rf} = 0dBm).

An excerpt of the complete characterization carried out on a shunt switch after growing doses of 1, 10, and 30Mrad(SiO_2) protons stresses, and during the subsequent room temperature anneal, is reported in Figure 2.

The most notable result is the heavy degradation of the insertion losses, see Figure 2, with just a small variation of the actuation voltage, see Figure 3. The relatively small variations of the actuation voltage with the increasing dose appears to exclude large charge trapping as the only cause for insertion losses degradation.

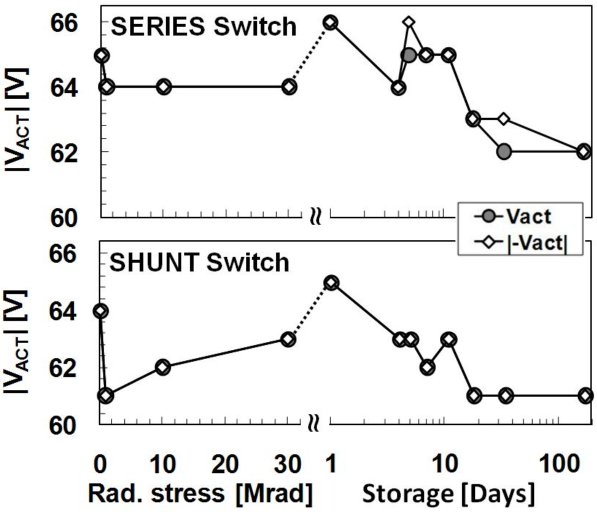

Figure 3: Evolution of V_{ACT} and $-V_{ACT}$ for a series switch (up) and a shunt one (bottom, from Figure 2) during the protons radiation stress and the successive days of storage.

In fact, positive charge trapping would have changed both the actuation and the release voltages toward lower values. Then charge de-trapping would have moved $|V_{ACT}|$ and $|V_{REL}|$ toward their pre-irradiation values. On the opposite, both follow a complex behavior with a fast degradation, a partial recovery during irradiation, and an apparent worsening during post-irradiation storage. Such a complex behavior suggests that the phenomena underlying the degradation of devices should have a complex nature, probably resulting from the superimposition of different effects having different temporal evolutions. This is confirmed by Figure 4, where we show the evolution of the S-parameters, which severely degrade during the storage (anneal).

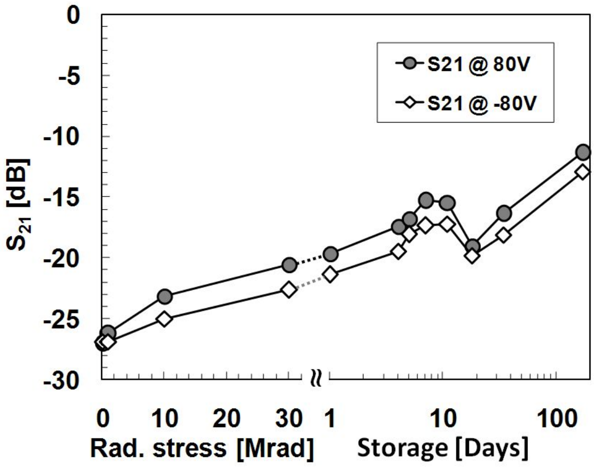

Figure 4: Evolution of the S_{21} parameter @ 80V and -80V extracted from curves of Figure 2.

It is believed that the degradation is not due to an increase of the coplanar waveguides (CPW) or substrate losses, since repeating the measurements at different frequency from 100kHz to 6GHz (also on simple CPW irradiated test structures) it does not show any frequency-related dependence, as shown in Figure 5.

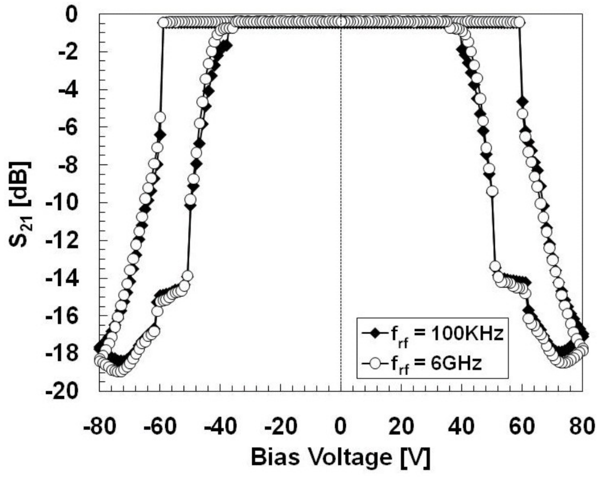

Figure 5: Comparison of S_{21} (V_{BIAS}) of a 30Mrad protons stressed shunt switch measured applying an rf signal of 100kHz, and 6GHz (P_{rf} = 0dBm). The curves are almost identical.

Furthermore, stressed devices have shown a faster degradation rate during cycling stresses (see Figure 6), and a possible explanation could be found in the degradation of the metal-to-metal contact (increased series resistance). In principle, the damage induced by 2MeV protons could be due to either displacement damage (lattice defects directly induced by proton-nucleus interactions), or to ionizing damage (protons generate columns of charges in the device that recombine and/or move generating the actual damage) [13].

Monte Carlo simulations with TRIM code [14] (see Figure 7) show that (i) the range of 2MeV protons is more than enough to cross all the device active area.

This confirms that protons are crossing the whole device, and that all parts (bridge, actuators, substrate) may in principle be the origin for the observed degradation; (ii) the displacement damage is mainly located in the bulk of the silicon. Since this part of the device has no role in the electrical performances of the switch, the easiest conclusion one can draw is that performance degradation should be linked someway to ionizing damage; (iii) however, displacement damage in the gold layer is much higher than that in the surface silicon, due to the larger mass of the former. Hence, a contribution of NIEL cannot be neglected.

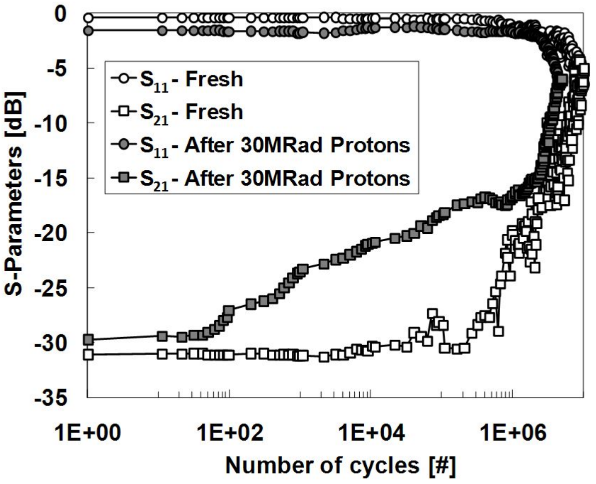

Figure 6: Comparison of the cycling robustness of an untreated series switch with a 30Mrad protons stressed one (V_{bias} = 80V, f_{rf} = 6GHz, P_{rf} = 0dBm).

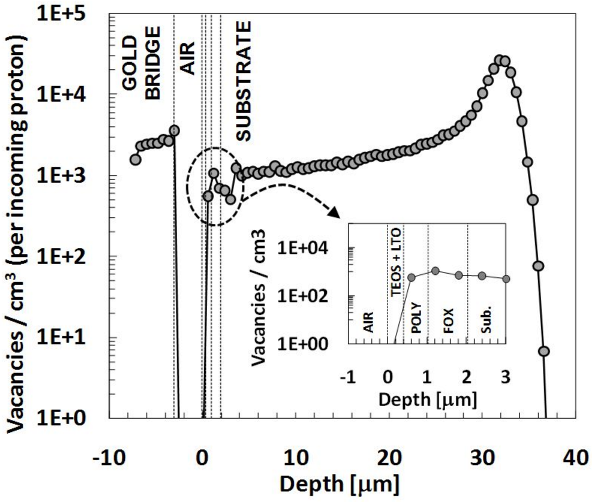

Figure 7: Monte Carlo TRIM simulation of displacement damage for 2MeV protons in our devices. The inset highlights the vacancies/cm^3 just below the air-gap.

The fluences used (up to 1.7×10^{13} for the higher dose) are actually compatible with literature results on displacement damage in silicon devices [15]. To shed a better light on this, we moved to a radiation source where displacement damage is in first approximation negligible, such as 10keV x-rays. 70 devices were tested with x-rays up to 1Mrad(SiO_2), and the summary of results are reported in Table 1.

Table 1: X-ray radiation stress induced failures. Number of tested devices: 30 meanders based, 40 straight beam.

Type of damage	*Meanders based suspensions failure [%]*	*Straight beams suspensions failure [%]*
Stiction	50	6
S-parameters degradation	42	24
Negligible variations	8	66
Actuation line damage	0	4

An interesting result is reported in Figure 8 (series switch), in which the radiation stress has degraded the S-parameters (S_{21} in on state), with almost no changes in both V_{ACT} and V_{REL}, and showing a good recovery after 1 month.

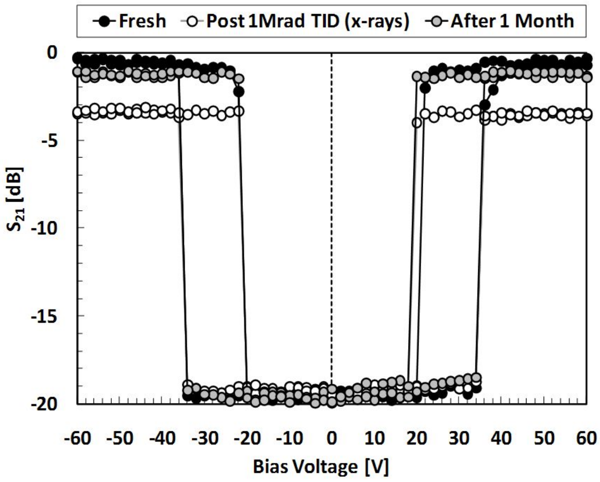

Figure 8: Comparison of $S_{21}(V_{BIAS})$ of a fresh shunt switch, after 1Mrad x-rays stress, and after 1 month of storage (showing the recovery).

This more pronounced recovery found after x-rays irradiation, if compared to protons, suggests that displacement damage may actually play a role in the degradation of switches performance. On the other side, recombination kinetics is not the same after irradiation with x-rays and protons (especially at relatively low energies such as those used here [13]), and phenomena purely linked to ionization damage cannot be excluded.

CONCLUSIONS

We have shown that RF-MEMS switches performances can be impacted by ionizing radiation. In particular, both the actuation voltage and the S-parameters are impaired.

The relatively small shift in actuation and release voltages do not appear as a limiting factor for the device reliability during operations, but the S-parameters degradations are potentially more critical, in particular as a consequence of the complex time evolution which complicate the development of a predictive model. Moreover, both NIEL and ionizing damage appear to play a role. Which one of the two is prevailing and why is still an open question which we will address with future works.

ACKWNOLEDGEMENT

Authors would like to thank Benno Margesin, Flavio Giacomozzi, and Jacopo Iannacci from FBK-IRST (Italy), and Roberto Gaddi (Cavendish Kinetics) for fruitful discussions and devices design and manufacturing. This work was partially supported by the Italian project PRIN 2005 entitled “Reliability of RF-MEMS for high frequency applications”.

REFERENCES

[1] G. Rebeiz, et al., “RF MEMS Switches and Switch Circuits”, IEEE Microw. Mag., Dec. 2001, pp. 59-71.

[2] H. C. Koons, et al., “The impact of the space environment on space systems”, TR-99(1670)-1, 1999, pp. 7-10.

[3] A. R. Knudsen et al., “The effects of radiation on MEMS accelerometers”, IEEE Trans. Nucl. Sci., 1996, vol. 43, pp. 3122.

[4] M. Exarchos et al., “Charging of Radiation Induced Defects in RF MEMS Dielectric Films”, doi:10.1016/j.microrel.2006.07.045

[5] S. S. McClure, et al., “Radiation Effects in Micro-Electro-Mechanical Systems (MEMS): RF Relays”, IEEE Trans. Nucl. Sci. 2002, vol. 49, pp. 3197.

[6] J. Ruan, et al., “Alpha particle radiation effects in RF MEMS capacitive switches”, Micr. Rel. 48 (2008), pp. 1241-1244.

[7] E. Stassinopoulos, et al., “The space radiation environment for electronics”, Proceedings of the IEEE, 76 (11), Nov. 1988, pp. 1423 – 1442.

[8] J. Schwank, “Total dose effects in MOS devices”, in IEEE NSREC Short Course, 2002.

[9] D. Ball, R. Schrimpf, H. Barnaby, “Separation of ionization and displacement damage using gate-controlled lateral PNP bipolar transistors”, IEEE Trans. on Nuclear Science, 49(6), 2002, pp. 3185-3190.

[10] R. Gaddi et. al, “Interdigitated Low-loss Ohmic RF-MEMS Switches”, NSTI 2004, Vol. 2, pp. 327-330.

[11] F. Giacomozzi, et al., “Electromechanical Aspects in the Optimization of the Transmission Characteristics of Series Ohmic RF-Switches”, MEMSWAVE 2004, pp. C25-C28.

[12] A. Tazzoli, et al., “Electrostatic Discharge and Cycling Effects on Ohmic and Capacitive RF-MEMS Switches”, IEEE Trans. on Device and Materials Reliability, vol. 7, no. 3, Sept. 2007, pp. 429-437.

[13] T. P. Ma, et al., “Ionizing radiation effects in MOS devices and circuits”, Wiley, New York, 1989.

[14] J. Ziegler, SRIM/TRIM computer code, available on line at www.srim.org.

[15] S. Messenger, et al., “Non-ionizing energy loss (NIEL) for heavy ions”, IEEE Trans. on Nuclear Science, 1999, pp. 1595-1602.