ECS Transactions, 23 (1) 279-285 (2009)
10.1149/1.3183730 ©The Electrochemical Society

Radiation Effects on SOI Microrelays for Space Applications

A. Lozano[a], F. Palumbo[b], M. Alurralde[c]

[a]INTI-Electrónica e Informática, Buenos Aires, Argentina
[b]CONICET-CNEA, Buenos Aires, Argentina
[c]CNEA, Buenos Aires, Argentina

Considerable effort has gone into the study of the failure mechanisms and reliability of micro-electro-mechanical-systems (MEMS) to extend its use to critical areas. In this paper a prototype of SOI microrelays is evaluated for space applications. The MEMS devices are subjected to uniform proton beam of 10MeV, while its response is monitored by electrical characteristics for successive irradiation pulses. Although the system shows a significant increase of positive trapped charge, it has not been found any limitation on the functionality based in the main parameters such as the actuation voltage, the leakage currents, and conduction mechanism of the switch.

1. Introduction

Micro-Electro-Mechanical System (MEMS) devices are rapidly maturing to extend their application to critical areas. The use of these technologies for space systems has been limited thus far due to concerns of reliability and qualifiability. Among all common failure mechanisms, such as fracture, stiction, and electromigration, the degradation of dielectrics layers is one of the limitation effects of the functionality and long-term survivability [1-4].

The dielectric charging due to the incident radiation is a major problem for the application of MEMS in space. The thickness reduction of the dielectric layer could be a possible way to face this problem increasing the leakage current. As traditional microelectronic devices, MEMS devices that are activated by electric fields across insulators are likely to be affected by high energy radiation effects through similar mechanisms [4-7]. Although few studies have been made on the effects of radiation on MEMS, all the available results indicate similar potential problems, such as single event dielectric rupture or bulk lattice damage leading to material rupture. Electrostatic attraction and fiction can potentially be aggravated by charging effects. Radiation-induced charging may enhance or contribute to microwelding, electrostatic clamping, or wear processes between two surfaces where small gaps or contacts occurs [5-6]. In this framework, the determination of the survivability of MEMS devices requires a complete analysis of the failure mechanism and reliability. In order to understand the reliability of any system, it is mandatory to know its failure behavior, and the factors that invoke this failure.

In this work, results focused on those objectives are shown presenting a radiation hardness analysis of an electrostatic comb drive structure manufactured on Silicon on Insulator (SOI) wafers. A detailed analysis of degradation is presented by using electrical characterization techniques to evaluate charge trapping and leakage currents on different regions of the structure. All experimental data are interpreted from the electrical point of view in terms of the physical mechanisms responsible for creation of the oxide-trapped charge, and the electrostatic charge that actuates the microrelay.

2. Experimental and Samples Details

The samples used into the experiment are MEMS microrelay structures based on a double-fold spring and a pair of comb drives arranged symmetrically at both sides of a movable lateral contact (Fig.1(a)). The application of voltage between fixed and movable comb fingers actuates the switch by mean of electrostatic forces. The details of the structure is shown in Fig.1(a). Different variants of the proposed design have been studied with a variation of the width of the cell ranging from 490 to 910 μm, including different number of fingers (ranging from 20 to 42) symmetrically distributed on both sides of the central contact. The space between the fixed and movable part of the central contact is 2 μm and the gap between fingers range from 2 to 4 μm. From all these variations, a particular set of devices has been chosen to be exposed to the radiation tests due to their lower actuation voltages.

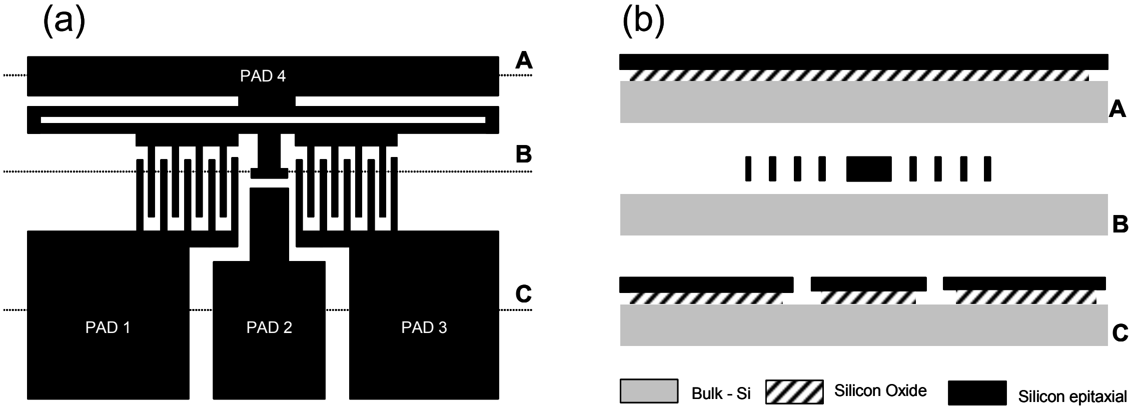

Fig.1: Basic detail of the microrelay structure. (a) Schematic diagram of the double-fold spring and a pair of comb drives arranged symmetrically at both sides of the movable lateral contact. (b) Cross section views of the microrelay structure. A, B and C are cross section of different regions of the structure.

The fabrication of prototypes was made using the surface micromachining process on epitaxied SOI (Epi-SOI) from TRONIC'S Microsystems through MPW (Multi Project Wafer) run service [8]. The main features of the technology are 20μm thick single crystal silicon active and 0.4μm thick sacrificial layers (SiO_2). The fabrication process based on SOI wafers allowed obtaining the complete design of the devices in only one mask. A parameterized hierarchical structure with the Cadence layout editor was used. Using the concept of “basic cells” structures, twenty-two different devices in the active wafer area were made easily through those basic cells, reducing considerably the design time. Cross section views in different regions of the microrelay structure are shown in Fig.1(b). The cross section labeled “A” and “C” correspond to the contact pads of the double-fold spring and of the comb drive respectively. In both cases it is observed that a dielectric layer isolate the pads contacts. On the other hand, as is shown in the cross section "B", the pair of comb drives is suspended without any dielectric layer below.

The threshold voltage (V_{th}) required to actuate the switch was measured for the different design variations of the devices. Depending on the different devices geometry, it ranges from 22V to 50V. In the case of microrelays with a reduced number of fingers on the comb drive and with shorter springs, the required V_{th} could reach higher values (around 90V), near to the breakdown field of the isolation layer. Such voltage level breaks the device and makes it useless, so those kind of was not tested.

To test the response under space applications conditions, different sets of samples have been subjected to uniform proton beam of 10MeV inside a vacuum chamber at the TANDAR accelerator (TANDEM Argentino) at CNEA (Comisión Nacional de Energía Atómica). After each irradiation pulse, electrical characterization have been performed using capacitance-voltage (C-V) and current-voltage (I-V) measurements to evaluate charge trapping and leakage current. Moreover, the variation of the actuation voltage has also been monitored as a function of the total dose.

3. Results and Discussion

The space radiation environment can be classified into two populations: trapped particles in magnetic belts and transient particles, mainly coming from solar events. In absence of sporadic solar particle events the radiation exposure in Low Earth orbit (LEO) inside spacecrafts is determined by the galactic cosmic radiation (protons and heavier ions) and by the protons inside the South Atlantic Anomaly (SAA), an area where the radiation belt comes closer to the earth and where the radiation levels are actually much lower than those at higher altitudes [9]. The analysis in this work is focused on the effects of the protons radiation in those low orbits using relatively low energy particles beam.

Based on the methodology described in the last section and the space environment concepts stated above, different sets of samples have been subjected to 10MeV proton beam with different total accumulated doses. Typical results of C-V measurements made on contact pads for each radiation dose in a microrelay with 30 fingers (3μm width and a gap of 3μm) are shown in Fig.2(a).

The capacitance is measured between the contact pad of the comb drive (pad 2 on Fig.1) and the p-type Si bulk. It is clear, from the curves of Fig.2(a), that the shift forward negative voltages as a function of the total dose corresponds to accumulation of positive charge in the stack. This results agree with those on MOS (Metal Oxide Semiconductor) structures where it is a well-know one of the main effects in the increase of positive trapped charge in the gate oxide after irradiation [10-11].

On the other hand, the voltage shift at constant capacitance as a function of total dose for several samples is shown in Fig.2(b). It is observed that the dynamic of radiation induced trap charge increases with doses and even at higher doses the charge trapping do not reach saturation. The trapping of charge in the SiO_2 layer could be accompanied by an increase of states in the $Si\text{-}SiO_2$ interface of the structure [10-11]. Although the discussion of long-term reliability is beyond the scope of this paper, it is important to consider this effect for future experiments.

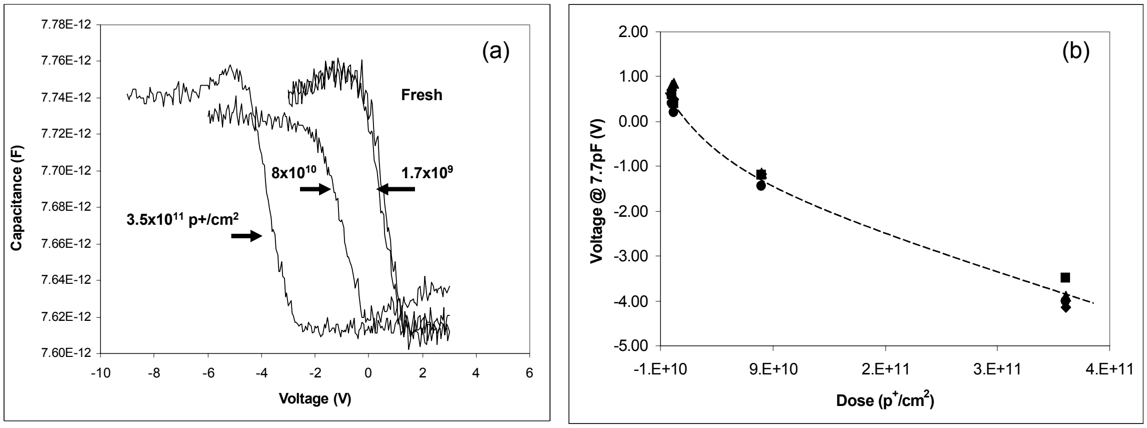

Fig.2. (a) Typical high frequency C–V curves subjected to different doses. The C-V curves are measured between the contact pad of the comb drive (pad 2 on Fig.1) and the p-type Si bulk. (b) Voltage shift of C-V curves for several samples as a function of accumulated dose. The voltage is calculated at constant capacitance value of 7.7pF. The samples has been subjected to 10MeV proton beam with different total accumulated doses.

The accumulation of radiation induced trapped charge shown in Fig.2 could limit the functionality of the microrelay structure. Due to the relative thickness of this dielectric layer, it is very sensitive to ionizing radiation [11-12]. A relatively small dose in a field oxide can induce sufficient charge trapping to cause field-oxide induced device failure. Charge buildup in the thick oxides could turns on a parasitic leakage path due to the increase of the depletion region next to the Si-SiO$_2$ interface. Current could flows from one pad to another affecting the electrostatic force created within the structures of the MEMS [10-12]. Because of that, the leakage levels between the pads of the double-fold spring and the comb drive are measured before and after radiation. Typical results of leakage current between pads of the double-fold spring and the comb drive are shown in Fig.3. It was measured before and after a radiation pulse of 10 MeV protons with a total dose of $3.5x10^{11}$ p^+/cm^2.

The measurements have been performed at low voltages (before the V_{th} of the switch) in order to evaluate also the static power supply current of the device with radiation. The later is an important aspect for space applications. It is clear from this result that even a worst-case radiation condition for radiation-induced charge buildup (as shown in Fig.3) does not affect the level of the leakage current between the pads of the microrelay structure.

Another important aspect to take into account is the variation of the threshold voltage as a function of the total dose. In our experimental conditions, and in the case of a microrelay with 30 fingers (3μm width and a gap of 3μm), the V_{th} has not shown significant variation in its nominal value of 23V ± 5%. A correlation of the conduction resistance, before and after a radiation pulse, is shown in the inset of Fig.3. It was measured in a range starting at lower voltages ($V<V_{th}$) up to higher voltage levels beyond the threshold voltage ($V>V_{th}$). It is clear that the conduction mechanism is also not affected by the incident beam.

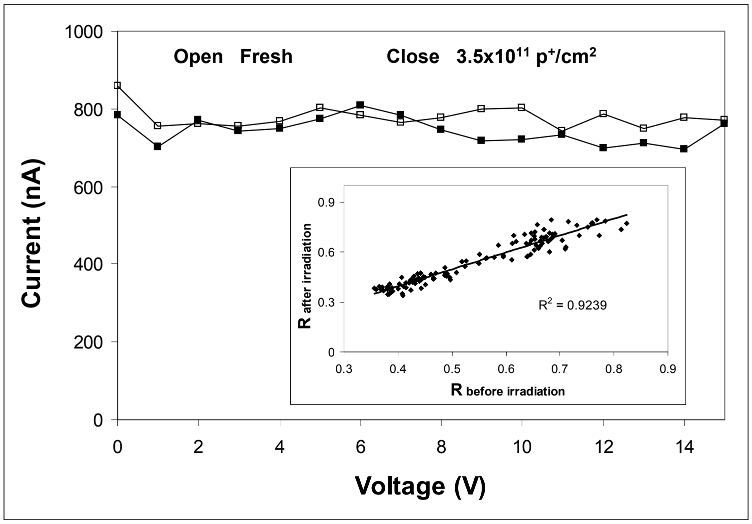

Fig.3. Typical measurements of leakage current between pads of the double-fold spring and the comb drive are measured before and after a radiation pulse. The inset shows a correlation of the normalized conduction resistance before and after a radiation pulse. The radiation pulse corresponds to a total dose of $3.5\text{x}10^{11}$ p^+/cm^2 of 10 MeV protons.

In general, the results obtained show that the irradiations with 10 MeV protons beam cause a significant increase of the positive charge in the dielectric layer of the microrelay structure. However, it has not been found any limitation on the functionality of the main parameters, such as the threshold voltage, the leakage current level between contacts of the pads of the double-fold spring and the comb drive, and conduction mechanism. Further analysis on long-term reliability must be conducted for a complete evaluation of the MEMS devices.

4. Radiation Effects on the Electrostatic Force

The motion of the comb drive is given by the electrostatic force created within the structures of the MEMS device. That force is originated by the total capacitance distributed on the comb fingers (air gap) Fig.1(a). The force lines at the end of each finger are added to create the total net force. This net force is the responsible of the fingers attraction only along the finger length for any polarity of the voltage difference applied between movable and fixed part of the comb drive. The resulting force does not depend on the fingers relative lengthwise position and it is constant for a constant voltage difference. Considering that the only electric field that contribute to the electrostatic force is along the fingers, the total capacitance can be written as:

$$C=n\frac{\varepsilon_0 A}{g} \qquad [1]$$

where n is the number of fingers, ε_0 is the dielectric constant for the fingers gap, A and g are the area and the separation respectively of the inter-finger lateral gap. Then, the total electrostatic force on a comb drive, F_e, is given by [13]:

$$F_e = \frac{1}{2} V^2 \frac{\partial C}{\partial x} = n \frac{h\varepsilon_0}{g} V^2 \qquad [2]$$

where h is the thickness of the fingers, and V the constant voltage difference. In order to actuate the switch to close the contact, the electrostatic force F_e must compensate the opposite spring force. In the case of rad-hard experiments, most radiation effects have been attributed to additional electrostatic force caused by charge accumulation in the dielectric layers of the structure (SiO_2 and/or Si_3N_4) [5]. Electrostatic attraction and friction can potentially be aggravated by charging effects. Particularly radiation-induced charging may enhance or contribute to electrostatic clamping, or wear processes between two surfaces where small gaps or contacts occur. The trapped charges could alter the electric field distribution around the capacitor which, in turn, led to changes to the output voltage as it was reported in other works [3]. In our case the irradiation cause a gradual increase of the trapped charge in the dielectric layer as the total dose increase. It is evident in the Fig.2 where the C-V curves shift significantly after each radiation pulse. But the voltage required to actuate the switch does not show any deviation from its initial value. This behavior could be explained by the analysis of the driving force. According to the previous description, it only depends on the variation of the capacitance between the combs arranged symmetrically (Fig.1(a)). Since the radiation mainly create positive trapped charge in dielectric layers, the absence of SiO_2 around the pair of comb drives minimize the effects on the operational voltage. A detailed description of the layers in three cross sections of the microrelay is shown in Fig.1(b). It is observed that the pair of comb drives doesn't have any dielectric layer below reducing the effect of the radiation-induced trapped charge. On the contrary, the induced charge clearly affects regions with dielectric layers, such as the contact pad (Fig.1(b)). As a consequence of that a serial parasitic capacitance appears. But, as it is explained in the equation of the electrostatic force, only the variation of the capacitance between the comb inter-fingers affects its magnitude. Finally, the results also show no presence of additional effects (such as electrostatic clamping) affecting the functionality of the device due to the radiation induced charge.

5. Conclusions

In this work aspects of design, process and validation of a prototype of microrelay have been studied under a 10MeV proton beam for space applications. The performance of the devices has been studied using electrical characterization techniques, measuring the trapped charge, leakage current and actuation voltage of the MEMS devices. It has been found that, even though the dielectric layer of the process shows a significant increase of radiation induced trapped charge, the functionality of the microrelay has not been affected. The unalterability of important parameters, such as the leakage current (between the contacts of the double-fold spring and the comb), and the operational voltage gives a strong indication that the design strategy could be adequate for rad-had applications. The proposed prototype of microrelay has been radiation operable at high radiation doses like total dose levels which are expected in a space environment. Further experiments of considering cycling and annealing effects are needed to evaluate the long-term reliability of the MEMS devices.

6. Acknowledgments

One of the authors (F.P.) gratefully acknowledges the economical support from the ICTP Associate Scheme, Trieste, Italy. F.P. is a researcher at CONICET. This work has been partially supported by ANPCyT, PICT05 N° 38255.

7. References

1. L. P. Schanwald, J. R. Schwank, J. J. Sniegowski, D. S. Walsh, N. F. Smith, K. A. Peterson, M. R. Shaneyfelt, P. S. Winokur, J. H. Smith, and B. L. Doyle, *IEEE Trans Nucl Sci* 45: 2789-2798 (1998).
2. C. I. Lee, A. H. Johnston, W. C. Tang, C. E. Barnes, and J Lyke, *IEEE Trans Nucl Sci 43* (6) 3 127-3 132 (1996).
3. A. R. Knudson, S. Buchner, P. McDonald, W. J. Stapor, A. B. Campbell, K. S. Grabowski, and D. L. Knies, *IEEE Trans Nucl Sci 43:* (6) 3 122-3 126 (1996).
4. M. Exarchos, E. Papandreou, P. Pons, M. Lamhamdi, G.J. Papaioannou and R. Plana, *Microelectronics Reliability* 46 1695–1699 (2006).
5. L.D Edmonds, G.M. Swift and C.I.Lee, *IEEE Trans.Nucl. Sci*., vol.45, pp.2779-2788, (1998).
6. Caffey, J.R.; Kladitis, P.E.; *17th IEEE International Conference on MEMS* 133 – 136 (2004).
7. T. F. Miyahira, H. N. Becker, S. S. McClure, L. D. Edmonds, A. H. Johnston and Y. Hishinuma, *IEEE. Trans. Nucl. Sci*., vol. 53, pp. 1860 (2003).
8. S. Renard, *Proc. SPIE*, vol. 4174, pp. 193-19, (2000).
9. J.L. Barth, C.S. Dyer, and E.G. Stassinopoulos, "Space, Atmospheric, and Terrestrial Radiation Environments," *IEEE Trans. Nuclear Science,* vol. 50, no. 3, pp. 466-482, June 2003.
10. T.R. Oldham, *Ionizing Radiation effects in MOS oxides*, (World Scientific 1999).
11. T. P. Ma and P. V. Dressendorfer, *Ionizing Radiation Effects In MOS Devices & Circuits* (John Wiley & Sons, New York, 1989).
12. N. S. Saks, M. G. Ancona, and J. A. Modolo, *IEEE Trans. Nucl. Sci*., vol. NS-31, p. 1249, (1984).
13. W. C. Tang, *Electrostatic Comb Drive for Resonant Sensor and Actuator Application,* PhD Dissertation, Department of Electrical Engineering and Computer Sciences University of California, Berkeley, CA, 1990.