SAND2014-1086C

The Susceptibility of TaO_x-based Memristive Devices to Continuous and Pulsed Ionizing Radiation

M. L. McLain[1], J. K. McDonald[1], T. J. Sheridan[1], G. R. Chantler[1], P. R. Mickel[1], D. Hanson[1], D. Hughart[1], and M. J. Marinella[1]

[1]Sandia National Laboratories, Albuquerque, NM

ABSTRACT:

The effects of continuous and pulsed ionizing radiation on tantalum oxide (TaO_x) memristors are investigated. This is the first dose rate study on any type of memristive memory technology. The data indicate that it is possible for the devices to switch from a high resistance off-state to a low resistance on-state in both total ionizing dose and dose rate environments.

Corresponding (and Presenting) Author:
Michael L. McLain
Sandia National Laboratories
P.O. Box 5800, MS 1167, Albuquerque, NM, 87185-1167
Phone: 505-844-6825
Email: mlmclai@sandia.gov

Co-Authors:

Kyle McDonald:	Sandia National Labs*	Email: jkmcdon@sandia.gov	Phone: 505-845-7939
Tim Sheridan	Sandia National Labs*	Email: tjsheri@sandia.gov	Phone: 505-845-7942
Patrick Mickel:	Sandia National Labs*	Email: prmicke@sandia.gov	Phone: 505-284-0865
Don Hanson	Sandia National Labs*	Email: djhanso@sandia.gov	Phone: 505-844-6969
Gary Chantler:	Sandia National Labs*	Email: grchant@sandia.gov	Phone: 505-845-1287
David Hughart:	Sandia National Labs*	Email: dhughar@sandia.gov	Phone: 505-845-7942
Matt Marinella:	Sandia National Labs*	Email: mmarine@sandia.gov	Phone: 505-844-3153

Session Preference: Radiation Effects on Devices and ICs
Presentation Preference: Oral

FUNDING STATEMENT
This work was funded by Sandia's Laboratory Directed Research and Development program. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

INTRODUCTION

The semiconductor community is continually pursuing novel technologies to replace static random access memory (SRAM), dynamic RAM (DRAM), and flash memories as Si-based technologies approach scaling limits. In recent years, several candidates have emerged as a possible replacement to current SRAM/DRAM/flash memories. One of the more promising technologies that has been identified by the International Technology Roadmap for Semiconductors (ITRS) is resistive RAM (also known as redox or memristive memory or ReRAM). ReRAM is comprised of an array of two terminal metal-insulator-metal memristors that are characterized by a low resistance on-state and a high resistance off-state depending on the electrical bias and bias history. Examples of commonly used insulators in memristive devices are tantalum oxide (TaO_x), titanium dioxide (TiO_2), and hafnium oxide (HfO_x). All of these materials are categorized as transition metal oxides (TMO).

Tantalum oxide memristors are attractive to the electronic industry because of excellent scalability, high endurance, high switching speed, and low voltage operation [1-3]. Note that the subscript x in TaO_x denotes that the material is substoichiometric tantalum pentoxide (Ta_2O_5). Shown in Fig. 1 are multiple hysteretic I-V loops for a formed TaO_x memristor used in this study. The moderate variation between consecutive hysteresis sweeps of the device is typical of these research devices. The arrows indicate the direction of the sweep and the labels specify the state of the memristor (i.e., high resistance off-state or low resistance on-state). The inset in Fig. 1 illustrates the cross-sectional stack of the memristor structure. It is hypothesized that the switching mechanism in TaO_x memristors involves redox reactions and the migration of O_2 anions and oxygen vacancies. These processes lead to the formation of a Ta-rich conducting filament of a certain radius [4], [5].

Given the potential use of TaO_x memristors in radiation-hardened electronics, it is imperative that we understand the radiation susceptibility of these devices. Several studies have investigated the impact of total ionizing dose (TID) and heavy ions on the electrical characteristics of TaO_x memristors [2], [3], [6-9]. However, the devices were floating in most of the previous experiments. In this summary, the TID and dose rate response of TaO_x memristors is investigated with the terminals floating, grounded, and biased during irradiation. This is the first study on the effects of pulsed ionizing radiation on any type of memristive technology.

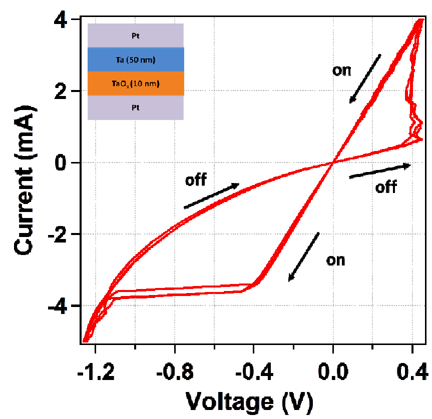


Fig. 1. Representative electrical characteristics of a TaO_x memristor swept multiple times. The arrows indicate the direction of the sweep. The inset is an illustration of the cross-section.

EXPERIMENTAL DETAILS

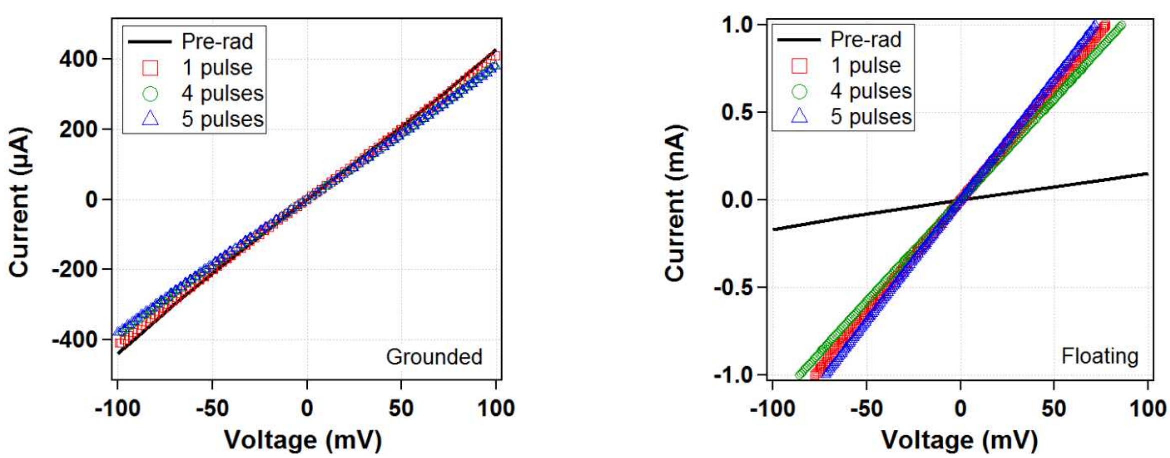
Two different TaO_x structures were investigated. One memristor structure consisted of four layers on top of a Si substrate/thermal oxide (180 nm)/Ti (5 nm) stack. The approximate TaO_x memristive layer thickness is 10 nm, the Ta layer is 50 nm thick, and the top and bottom platinum (Pt) electrodes are 10 nm and 30 nm thick, respectively. The Pt electrodes were electron beam evaporated with a shadow mask technique that resulted in isolated top and bottom electrodes patterned into "dog-bone" structures (i.e., two contact pads per electrode). When vertical and horizontal "dog-bone" electrodes intersect, a functional memristor is formed with a nominal cross-sectional area of 10 µm x 10 µm. These memristors are similar to the devices described in [2], [9]. Another structure that consisted of a 15 nm thick Ta layer and 20 nm thick TiN electrodes was also tested. These memristors were two terminal devices. All of the memristors were screened prior to the experiments to ensure proper functionality. A more complete description of the device fabrication process and structures will be provided in the final paper

A Scandiflash flash X-ray source and a linear accelerator (LINAC) were used to study the impact of pulsed ionizing radiation on the devices. The dose rate in these experiments ranged from ~5×10^7 rad(Si)/s to ~4.7×10^{8} rad(Si)/s. The Scandiflash is capable of providing a 600 keV, 35 ns X-ray dose output. The LINAC provides a nominal electron energy of 20 MeV for varying pulse widths (50 ns ≤ PW ≤ 500 ns) and dose rates. Thermoluminescent detectors (TLDs), photoconductive detectors (PCDs), and calorimeters were used to determine the dose and dose rate. Multiple devices were tested with each radiation source. During irradiation, the devices were floating, grounded, or biased. In the majority of the experiments, the devices were switched into the high resistance off-state prior to being irradiated because this appears to be the more susceptible state. However, the devices were also tested in the low resistance on-state as well as intermediate resistance states.

The TID experiments were conducted using a cobalt-60 (^{60}Co) decay photon source that emits two distinct gamma (γ) rays at energies of 1.1732 MeV and 1.3325 MeV. These experiments were performed at a dose rate of approximately 650 rad(CaF_2)/s. All devices were placed in a mil-standard lead-aluminum box during irradiation. The temperature was monitored with a thermocouple and controlled with a Vortec cooler to ensure that the temperature did not vary significantly during the experiment. The TID levels listed in this summary are likely an overestimate of the dose because the majority of the energy deposited will not be in the memristive layers of interest [10]. In the final paper, 1-D radiation transport calculations will be utilized to convert the dose determined by the TLDs to the dose deposited (i.e., energy deposited) in the memristive layers. Multiple TaO_x-based devices with varying on-state and off-state resistances were irradiated in the ^{60}Co gamma irradiation chamber. The resistance values were calculated at an applied bias of 50 mV. During the ^{60}Co exposures, either all terminals on the devices were grounded or the top electrode was biased with a 1 Hz square wave with an amplitude of ± 100 mV and the bottom electrode was grounded.

RESULTS AND DISCUSSION

Shown in Fig. 2(a) and Fig. 2(b) are representative plots of four point probe read measurement data for two devices tested with the Scandiflash source. In these experiments, the devices were reset into the off-state and the dose rate was held constant at ~3×10^{8} rad(Si)/s. The read measurements were performed after a single X-ray pulse, after four consecutive X-ray pulses, and after five consecutive X-ray pulses using a HP 4155C parameter analyzer. If it was determined that there was a radiation-induced resistance change in the post-irradiation read measurements, the device was reset back into the original state. Note that in a read measurement, the voltage is swept over a finite range to ensure that the measurement does not change the state of the device. During irradiation, the terminals of the memristors were grounded (Fig. 2(a)), floating (Fig. 2(b)), or shorted together and left floating (not shown). The data in the plots suggest that the test condition influenced the radiation response. In particular, when the devices were floating

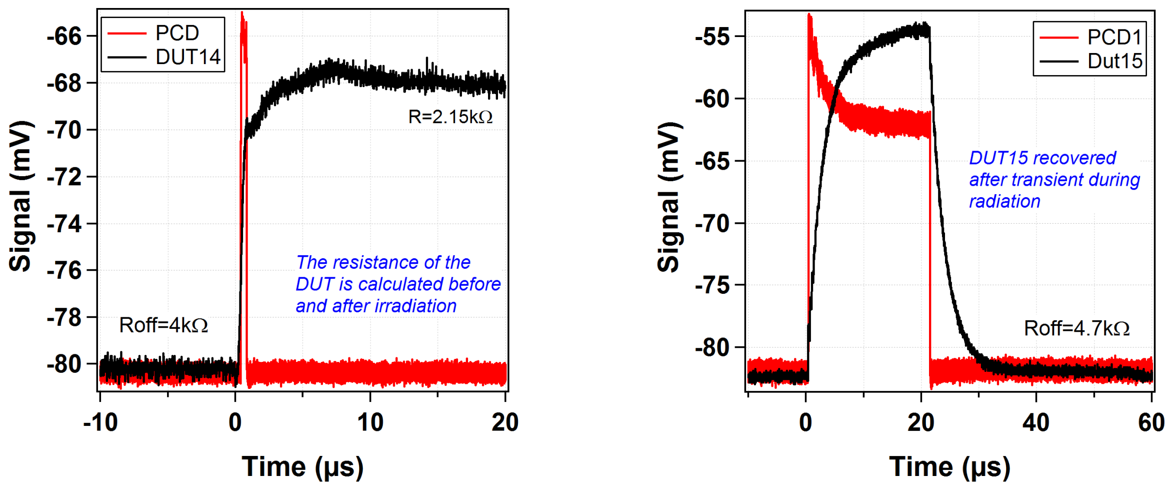


(a) (b)

Fig. 2. Plots of the pre- and post-irradiation read sweeps for two separate devices. The devices were either (a) grounded or (b) floating during irradiation. The dose rate was ~3×10^{8} rad/s. Read measurements were performed after a single X-ray pulse, after four consecutive X-ray pulses, and after five consecutive X-ray pulses.

during irradiation, two of the four devices changed from a high resistance off-state to a low resistance on-state. However, when the devices were grounded or shorted together and left floating, a resistance change was not observed in any of the memristors. The increased susceptibility in the floating case is likely a consequence of the inability of generated charge to exit sensitive regions of the device.

The purpose of the LINAC experiments was to investigate the effects of dose rate and dose on two terminal TaO_x memristors. During the pulsed electron irradiations, concurrent scope measurements captured radiation-induced transients and shifts in the resistance as a function of time. The RF signature produced by the LINAC was accounted for in the transient data presented here. Shown in Fig. 3(a) and Fig. 3(b) are representative plots of the transient data for two devices. The dose rate was ~4.7×10^8 rad(Si)/s, the radiation pulse width was 500ns or 20µs, and the bias during irradiation was -0.1V. The resistance values are calculated from the measured voltage. Similar to the Scandiflash results, there was variation in the dose rate response between devices and all devices remained functional following the electron beam exposures. Indeed, DUT14 had a radiation-induced resistance change following the pulsed exposure. In the final paper, more results from other devices and a detailed analysis will be provided.

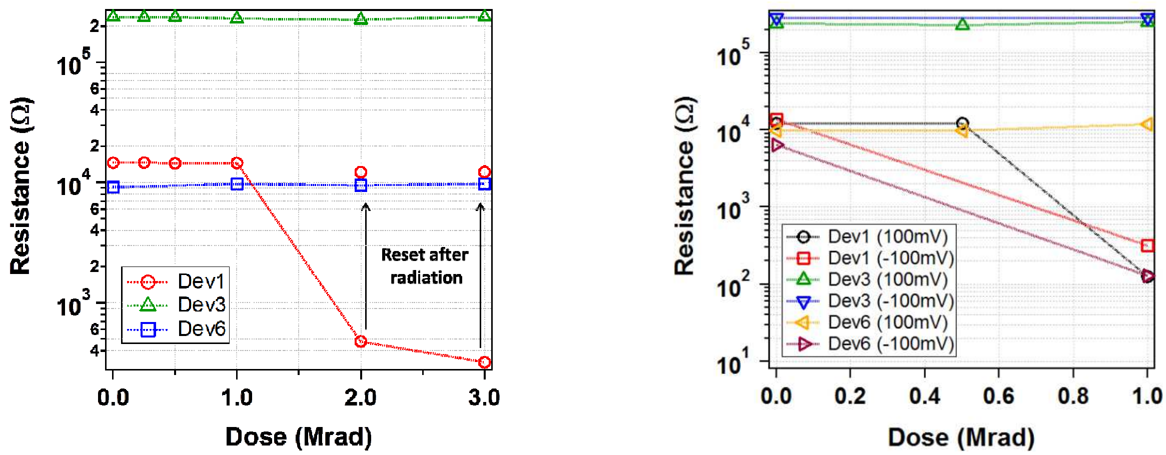


(a) (b)

Fig. 3. Plots of the measured voltage across (a) DUT14 and (b) DUT15 for two different pulsed exposures (500ns and 20µs). The PCD signal has been normalized to show when the radiation pulse occurs. The dose rate was ~4.7×10^8 rad(Si)/s.

The resistances of each device tested during grounded and biased ^{60}Co γ-ray experiments are plotted as a function of dose in Fig. 4(a) and Fig. 4(b), respectively. In Fig. 4(a), the doses listed on the x-axis are cumulative TID levels. In Fig. 4(b), the doses listed on the x-axis refer to the step stress levels and not the cumulative TID levels. The resistance values were determined at a voltage of ~50 mV. As indicated by the data, Device #1 has a significant decrease in resistance after every 1 Mrad step stress during the grounded experiments. When the polarity of the applied bias was positive, Device #1 also had a radiation-induced resistance change when the step stress was 1 Mrad(CaF_2). However, Devices #3 and #6 did not exhibit a resistance lowering when grounded or with a positive bias. When the polarity of the applied bias was negative, Devices #1 and #6 had a radiation-induced resistance change when the step stress was 1 Mrad(CaF_2), but Device #3 did not exhibit a resistance lowering. One possible reason for the observed bias dependence in two of the devices is that the applied bias will impact the transport of O_2 anions and oxygen vacancies. Despite the radiation-induced resistance changes, all of the devices could be reset into a high resistance off-state and were still fully functional following the radiation exposures.

The data obtained from the ionizing radiation experiments indicate that it is possible for the devices to switch from a high resistance off-state to a low resistance on-state after a TID step stress threshold has been surpassed. If a read measurement is performed prior to reaching the charge threshold, the devices 'reset' back to a pre-irradiation state. This suggests that the devices do not have a cumulative TID effect. It is also apparent that these devices are minimally affected by step stress TID levels less than 1 Mrad and that the TID threshold level at which the devices switch resistance states varies from device to device. It is currently unknown what factors contributed to the increased vulnerability in those devices. However, it is theorized that the ionizing radiation creates a local electric field within the TaO_x layer that aids in the transport of oxygen vacancies and anions, leading to the formation of a filament and a change in resistance.



(a) (b)

Fig. 4. Plots of the device resistance versus dose for the (a) grounded and (b) biased ^{60}Co experiments. The doses in (a) are cumulative TID levels and in (b) are step stress levels. The resistances were calculated at a voltage of ~50 mV.

CONCLUSION

In this summary, the effects of continuous and pulsed ionizing radiation on TaO_x memristors were investigated. The experiments were performed using a Scandiflash X-ray source, a LINAC in electron beam mode, and a ^{60}Co decay photon source. The pulsed experiments were the first dose rate studies performed on any type of memristive memory technology. The data indicate that it is possible for the devices to switch from a high resistance off-state to a low resistance on-state due to TID and pulsed ionizing radiation. Furthermore, the likelihood of a state change appears to be dependent on the experimental conditions. For example, when the terminals of the memristor were left floating during irradiation, it appeared that the devices were more susceptible and changed resistance states at much lower dose rates. This is likely a consequence of the inability of generated charge to exit sensitive regions of the device. Despite the radiation-induced resistance changes observed in some of the devices, the memristor radiation performance was promising and could potentially enable the discovery of a radiation-hardened nonvolatile memory technology.

REFERENCES

[1] M.-J. Lee, C. B. Lee, D. Lee, S. R. Lee, M. Chang, J. H. Hur, Y.-B. Kim, C.-J. Kim, D. H. Seo, S. Seo, U. I. Chung, I.-K. Yoo, and K. Kim, "A fast, high-endurance and scalable non-volatile memory device made from asymmetric Ta_2O_{5-x}/TaO_{2-x} bilayer structures," *Nat Mater,* vol. 10, no. 8, pp. 625-630, 2011.

[2] M. J. Marinella, S. M. Dalton, P. R. Mickel, P. E. D. Dodd, M. R. Shaneyfelt, E. Bielejec, G. Vizkelethy, and P. G. Kotula, "Initial assessment of the effects of radiation on the electrical characteristics of TaO_x memristive memories," *IEEE Trans. Nucl. Sci.,* vol. 59, no. 6, pp. 2987-2994, 2012.

[3] D. R. Hughart, A. J. Lohn, P. R. Mickel, S. M. Dalton, P. E. Dodd, M. R. Shaneyfelt, A. I. Silva, E. Bielejec, G. Vizkelethy, M. T. Marshall, M. L. McLain, and M. J. Marinella, "A comparison of the radiation response of TaO_x and TiO_2 memristors," *IEEE Trans. Nucl. Sci.,* vol. 60, no. 1, pp. 4512-4519, Dec. 2013.

[4] P. R. Mickel, A. J. Lohn, B. J. Choi, J. J. Yang, M.-X. Zhang, M. J. Marinella, C. D. James, and R. S. Williams, "A physical model of switching dynamics in tantalum oxide memristive devices," *Applied Physics Letters,* vol. 102, no. 22, pp. 223502-5, 2013.

[5] R. Waser, R. Dittmann, G. Staikov, and K. Szot, "Redox-Based Resistive Switching Memories – Nanoionic Mechanisms, Prospects, and Challenges," *Advanced Materials,* vol. 21, no. 25-26, pp. 2632-2663, 2009.

[6] D. R. Hughart, S. M. Dalton, P. R. Mickel, P. E. Dodd, M. R. Shaneyfelt, E. Bielejec, G. Vizkelethy, and M. J. Marinella, "Total ionizing dose and displacement damage effects on TaO_x memristive memories," in *Aerospace Conference, 2013 IEEE*, 2013, pp. 1-10.

[7] Z. Lijie, H. Ru, G. Dejin, Y. Pan, T. Poren, T. Fei, C. Yimao, and W. Yangyuan, "Total ionizing dose (TID) effects on TaO_x-based resistance change memory," *Electron Devices, IEEE Transactions on,* vol. 58, no. 8, pp. 2800-2804, 2011.

[8] E. Atanassova, A. Paskaleva, R. Konakova, D. Spassov, and V. F. Mitin, "Influence of γ radiation on thin Ta_2O_5–Si structures," *Microelectronics Journal,* vol. 32, no. 7, pp. 553-562, 2001.

[9] M. McLain, D. Hughart, D. J. Hanson, and M. J. Marinella, "Effects of Ionizing Radiation on TaO_x-based Memristive Devices (invited paper)," in *IEEE Aerospace Conference*, Big Sky, Montana, 2014.

[10] E. DeIonno, M. D. Looper, J. V. Osborn, H. J. Barnaby, and W. M. Tong, "Radiation effects studies on thin film TiO_2 memristor devices," in *2013 IEEE Aerospace Conference* 2013, pp. 1-8.