SAND2013-8999C

Radiation-Induced Resistance Changes in TaO_x and TiO_2 Memristors

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
Sandia National Laboratories
Albuquerque, NM 87123
dhughar@sandia.gov
mmarine@sandia.gov

***Abstract*—TaO_x and TiO_2 memristors have been irradiated with 800 keV Ta ions, 28 MeV Si ions, and 10 keV X-rays. Displacement damage effects are studied using 800 keV Ta ions and both technologies show changes in resistance for fluences greater than 10^{10} cm^{-2}. TaO_x devices show gradual resistance degradation in the off-state with increasing fluence. TiO_2 devices show gradual inconsistent increases in off-state resistance with inconsistent abrupt decreases. TaO_x devices show more stability and consistent off-state resistances than TiO_2 devices. Ionization effects are investigated using 28 MeV Si ions and 10 keV X-rays. During 28 MeV Si irradiation, both technologies change from the off-state to the on-state when a critical ionizing dose is reached without applying voltage or current to the device. The critical threshold is calculated using SRIM to be on the order of 60 Mrad(Si) or higher. 10 keV X-ray irradiation of doses up to 18 Mrad(Si) per step show little effect on either technology.**

TABLE OF CONTENTS

1. INTRODUCTION

Resistive RAM (ReRAM) is of great interest as a potential successor to current memory technologies as they become increasing limited by scaling [1-2]. ReRAM is composed of memristors, which generally consist of an insulator between two metal terminals that changes resistance based on applied currents and voltages. This results in a hysteresis loop, an example of which is shown in Fig. 1 for a TaO_x memristor. Applying a large enough current or voltage can change the resistance of the memristor. The change in resistance may be caused by changes in the radius of a conducting filament in the oxide layer of the device and the change in oxygen vacancies within that filament [3-5]. A high resistance state is often referred to as the off-state and a low resistance state as the on-state. By applying voltages/currents that are smaller than the threshold required to change the resistance, the current resistance of the device can be determined without altering it.

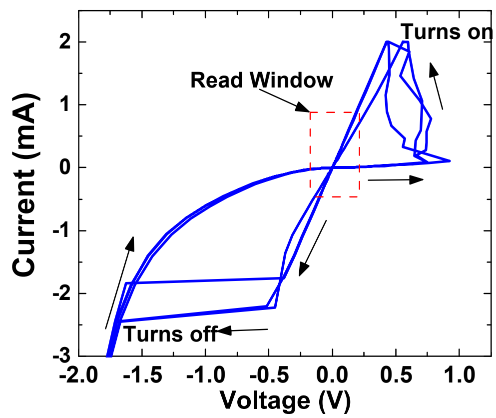

Fig. 1. Typical I-V curve with multiple loops for a TaO_x memristor with an example "read window" drawn [9].

There has been interest in evaluating the radiation response of memristors for potential use as memory in radiation-hardened electronics. Common choices of materials for memristors include oxides formed from tantalum, titanium, and hafnium, and the radiation response of all three materials is currently being investigated. Initial experiments on TiO_2 memristors reported little effect on resistance values after irradiation with Co^{60} gamma rays and 941 MeV Bi ions [6]. Another study found that TiO_2 devices showed no significant change in off-state resistance after being irradiated with 1 MeV alpha particles to a fluence of 10^{14}

978-1-4673-1813-6/13/$31.00 ©2013 IEEE

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

cm^{-2}, but off-state resistance decreased at a fluence of 10^{15} cm^{-2}, likely due to oxygen vacancy creation (devices were still able to switch resistance states afterwards) [7]. Further experiments have shown a high tolerance for radiation [8]. TaO_x memristors showed gradual off-state resistance decreases when exposed to 800 keV Si ions, also attributed to oxygen vacancy creation via displacement damage [9]. Co^{60} irradiation up to 500 krad(Si) showed little effect on TaO_x devices, but 10 keV X-ray exposures at a dose as low as 10 krad(Si) caused devices to switch from the off-state to the on-state [9]. Studies on HfO_2 have showed little effect from proton and Co^{60} irradiations [10-12].

In this paper we study the effects of ionization and displacement damage on TaO_x and TiO_2 memristors. Both technologies were irradiated with 800 keV Ta ions, 28 MeV Si ions, and 10 keV X-rays. Displacement damage causes gradual changes in resistance in each technology and ionization effects cause an abrupt change from the off-state to the on-state.

2. Experimental Details

A "random shadow mask" technique was used to make the memristors for this experiment, creating isolated individual crossbars with roughly 30% of the bars crossing. A memristor is formed where a vertical and horizontal "dogbone" electrode cross, serving as the top and bottom electrodes respectively. The nominal device dimensions were 10 µm x 10 µm. The approximate TaO_x insulating layer thickness was 10 nm. There was a 10 nm layer of platinum and 50 nm of tantalum above the oxide layer and a 30 nm platinum contact on the bottom, the same structure as presented in [9]. However, the devices used in this work are from a different manufacturing batch. For TiO_2 devices, the TiO_2 layer thickness was approximately 28 nm with a 30 nm platinum electrode on top and a 15 nm platinum electrode on the bottom. The TaO_x parts irradiated with 800 keV Ta ions and 28 MeV Si ions come from the same wafer and the X-ray irradiations used parts from that wafer and an additional wafer. The TiO_2 devices irradiated with heavy ions and X-rays come from the same wafer.

Several memristor die were packaged in standard 28 and 40 pin DIPs; a typical sample had six devices bonded. Some memristors can wear out over time, where off-state resistance changes over time until it is similar to the on-state resistance [13]. In order to make sure any failures were due to irradiation, devices were switched numerous times prior to experiments, and only devices without significant degradation of the off resistance were chosen for use in radiation experiments.

The parts used in this study were research devices and there was variation between the parts. Off-state resistances for the TaO_x parts typically ranged from a few kilo-ohms to tens of kilo-ohms. On-state resistances were generally one hundred to two hundred ohms. Typical TaO_x devices showed hysteresis loops similar to Fig. 1, though there was some variation between parts due to differences in off-state resistance. Devices that showed variations in resistance significantly larger than 10% from loop to loop generally failed within the first five to ten loops. Devices that did not exhibit this characteristic were looped for numerous cycles, typically about twenty to thirty times (though some parts were cycled more than fifty times), and there were no such changes (though off-state resistances often showed ~10% variation). The devices that were tested in these experiments showed stable and consistent (within 10% variation) off-state resistance values during hysteresis loops prior to irradiation.

There were larger variations in off-state resistance for TiO_2 parts (stable parts could vary by up to 20%) and some parts exhibited off-state resistance degradation. In those cases, the off-state resistance would decrease after each loop, degrading one to two orders of magnitude over five to ten loops. Typical starting off-state resistance values for TiO_2 devices were tens of kilo-ohms to hundreds of kilo-ohms and on-state resistances were four hundred to five hundred ohms. The TiO_2 devices tested in this work showed consistent off-state resistance values that did not vary more than 20% and did not show pre-rad off-state resistance degradation.

An Agilent 4156C Semiconductor Parameter Analyzer was used for electrical measurements. Typically, a 50 mV read measurement was made after each shot and a full set/reset characterization was performed following a series of irradiations. Resistance values were taken to be the resistance at 25 mV during a read sweep. The 4156C was in voltage force mode for the read sweeps. For the hysteresis loops, the 4156C was in current force mode and devices were set into the on-state using 3 mA and reset to the off-state using -4 mA for TaO_x devices. The TiO_2 devices were set into the on-state using 2 mA and reset to the off-state using -3 mA.

The elongated electrodes added series resistance that was often several kilo-ohms, causing the voltage across the force terminals to be higher than the voltage across the device. A four point measurement technique was used to separate the series resistance from the resistance of the memristor, in the same manner as [9]. One set of electrodes supplied the current through the device and the other set measured the voltage drop across the device.

Heavy ion irradiations were performed at the SNL Ion Beam Laboratory (IBL). To study the effects of displacement damage we used an 800 keV Ta beam, for which we expected 4.83 vacancies/ion/Å in the critical oxide region of the devices compared to 8.9×10^{-3} vacancies/ion/Å for the 28 MeV Si beam. For ionization studies we used a 28 MeV Si beam, which produced significantly more ionization than the 800 keV Ta beam. This combination allows us to start understanding and separating the effects due to ionization and displacement damage. The beam was focused to a 0.032 cm^2 spot size which covered the entire 10 μm x 10 μm device. The irradiation was performed in vacuum at approximately 10^{-6} torr. The device was cycled (put through the full set/reset loop) pre-rad prior to pumping down to vacuum and then reset to a high resistance state. Electrical measurements were made in situ, with read measurements taken between each irradiation without disturbing the chamber vacuum. Pins were floating during irradiation. The devices were not cycled in vacuum, as previous devices sometimes failed under those conditions.

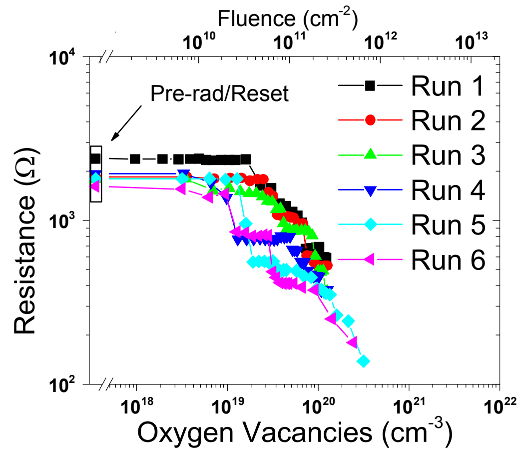

Fig. 2. Resistance versus average oxygen vacancy concentration for a TaO_x memristor irradiated with 800 keV Ta ions. The part was reset between each run [15].

3. Tantalum Oxide Results

800 keV Ta Ions

Five TaO_x memristors were irradiated with 800 keV Ta ions. Fluence values have been converted to the average concentration of oxygen vacancies created in the insulating layer, and ionizing dose delivered to the insulating layer. Conversions were calculated using SRIM assuming an oxide layer of Ta_2O_5 [14]. The calculations were performed using SRIM 2012 with full cascade calculations for 10,000 particles. The ionizing dose calculation was calculated in rad(Si) and we note that the actual value will be lower since charge yield effects were not taken into account. This means that some percentage of the electron-hole pairs created will recombine immediately, so the actual dose will be lower than the calculated dose. Without further experiments the magnitude of the effect is difficult to estimate. However, the current results provide a useful relative indication of ionizing dose to facilitate comparison between devices tested with 800 keV Ta and 28 MeV Si ions.

Fig. 2 plots the resistance of a representative TaO_x device versus the calculated average concentration of oxygen vacancies created during irradiation on the bottom x-axis. The fluence is shown on the top x-axis. The runs plotted in the figure are for a single device. Read sweeps were applied between each shot and a full set/reset cycle was applied between each run. The off-state resistance gradually degrades once the average concentration of oxygen vacancies reaches $\sim10^{19}$ cm^{-3} (a fluence of $\sim2\times10^{10}$ cm^{-2}). This threshold is not entirely consistent, as later runs tend to degrade at lower fluences than earlier runs. Runs four, five, and six begin degrading at roughly half of the fluence of earlier runs and show larger initial drops in resistance at the onset of degradation. These behaviors may be indicative of cumulative degradation that persists even after the device is reset. The fact that the reset process does not completely restore the off-state resistance between runs also supports this.

28 MeV Si Ions

TaO_x memristors were also irradiated with 28 MeV Si ions. As before, a read sweep was applied between each individual shot unless otherwise noted, and a full set/reset cycle was applied between each run in the irradiation sequence. Compared to 800 keV Ta, 28 MeV Si ion irradiation produces more electron-hole pairs that can potentially be trapped at defects (like oxygen vacancies) and build up in insulating regions. Since applying a read sweep may remove charge that is building up in the devices, Fig. 3(a) plots resistance versus the calculated dose delivered per shot (which may be viewed as the dose delivered between read sweeps since a sweep was performed after every shot for the data plotted). When the dose delivered between sweeps reaches roughly 60-120 Mrad(Si) as calculated by SRIM, the resistance changes dramatically. This is marked as the critical dose threshold in Fig. 3(a). This is a consistent threshold that is seen repeatedly over five separate runs. Most of these runs had different total doses that range from 120 Mrad(Si) to 1.2 Grad(Si) and when the data is re-plotted in terms of off-state resistance versus total dose per run in Fig. 3(b), no similar threshold is evident. A sixth run was also performed and the final three shots were all 60 Mrad(Si) (i.e. less than the critical dose per shot threshold), however, there was no read sweep applied between the final two shots. The first 60 Mrad(Si) shot showed no change in resistance when a read sweep was applied. After two consecutive shots of 60 Mrad(Si) with no read sweep between them, the device had switched on, just as in the cases when 120 Mrad(Si) was delivered in a single shot. This suggests that applying a read sweep can prevent this resistance change, likely by removing charge from the device. Additionally, the time between shots is on the order of minutes, so there is no apparent time dependence on that time scale. This further reinforces that the critical parameter

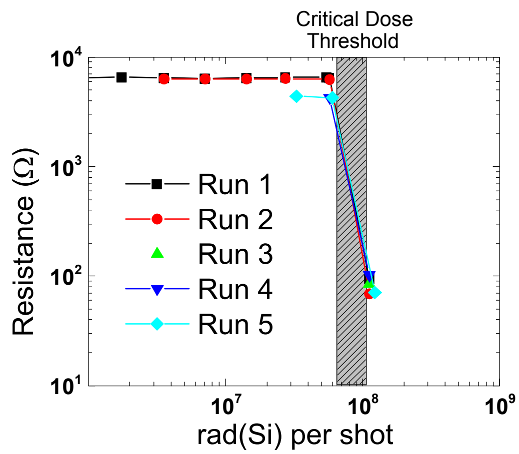

Fig. 3(a). Resistance vs. rad(Si) per shot for a TaO_x memristor irradiated with 28 MeV Si ions. The part was reset between runs. Duplicate shots are omitted for a given run. The dose per shot threshold appears to be in the range of 60-120 Mrad(Si) [15].

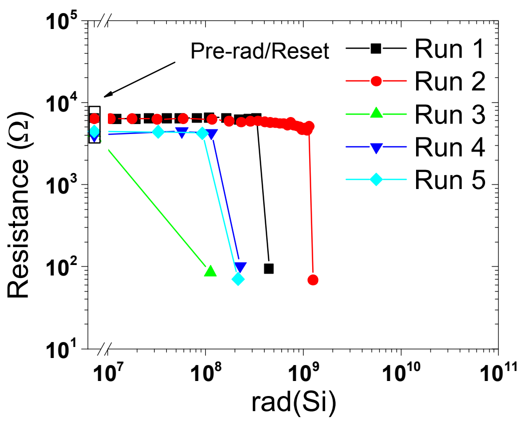

Fig. 3(b). Resistance vs. rad(Si) for a TaO_x memristor irradiated with 28 MeV Si ions. The part was reset between runs. The dose is cumulative for a given run. There is not a clear total dose threshold [15].

is the dose deposited without any voltage or current applied to the part and that even a 50 mV read sweep can prevent the change in resistance seen in Figs. 3(a) and (b).

The change in resistance happens abruptly, in contrast to the gradual changes seen from the 800 keV Ta irradiation. Also, the change is much larger in magnitude. Once these devices reach a certain dose per shot threshold, the device switches to a resistance in the on-state range. The device consistently switches to the same resistance (~80Ω) in every run. Resetting the device returns it to the initial off state with fairly little apparent accumulated damage, unlike the device in Fig. 2. The oxide region of the device is relatively shallow compared to the range of the typical 28 MeV Si ion, as a result the energy loss of the ions is primarily in

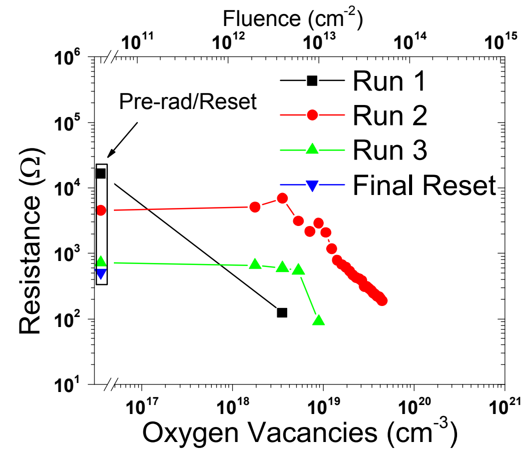

Fig. 4. Resistance versus average oxygen vacancy concentration for a TaO_x memristor irradiated with 28 MeV Si ions. The part was reset between each run [15].

electronic stopping power (or ionization) with a small fraction of the ions generating recoils (or displacement damage). Since the 28 MeV Si beam produces almost three orders of magnitude fewer oxygen vacancies for a given fluence, the off-state resistance does not degrade in Figs. 3(a) and (b) as it does in Fig. 2. The abrupt switch from off-state to on-state is likely caused by charge buildup due to ionization effects whereas the gradual degradation is due to oxygen vacancy creation through displacement damage.

One TaO_x device was irradiated to high enough fluences of 28 MeV Si ions that the calculated oxygen vacancy concentration was comparable to the 800 keV Ta irradiations. Both types of radiation-induced resistance changes seen thus far are observable in Fig. 4, which plots resistance versus calculated oxygen vacancy concentration on the bottom x-axis and fluence on the top x-axis. In this experiment, the first and third runs end with an abrupt change consistent with the resistance changes due to ionization in Fig. 3(a), whereas the second run shows gradual resistance degradation similar to the changes seen in Fig. 2 due to displacement damage. The dose for every shot in run two is 550 Mrad(Si), whereas the dose for the final shots of runs one and three is 1.1 Grad(Si), indicating that the critical dose threshold for this part is likely between 550 Mrad(Si) and 1.1 Grad(Si). The threshold for switching due to ionization is roughly an order of magnitude higher than the threshold for the part in Fig. 3(a). Since these are research quality devices the difference may be due to part to part variation. For the second run, the dose per shot remains below the threshold for switching due to ionization and shows gradual resistance degradation similar to the parts irradiated with 800 keV Ta. The resistance begins to degrade at a fluence of $\sim 6\times 10^{12}$ cm^{-2}, which corresponds to a calculated oxygen vacancy concentration of $\sim 5.5\times 10^{18}$ cm^{-3}, similar to the threshold of $\sim 10^{19}$ cm^{-3} observed for 800 keV Ta irradiation in Fig. 2. This is more evidence that the gradual resistance degradation seen in these experiments is due to oxygen vacancies created by displacement damage. The similar threshold also suggests that ionization effects may not have a significant impact on the resistance degradation caused by displacement damage.

4. Titanium Oxide Results

800 keV Ta Ions

Five TiO_2 memristors were also irradiated with 800 keV Ta ions. Unlike the TaO_x memristors, there was not a consistent gradual decrease in resistance with increasing fluence. Fig. 5 plots resistance versus calculated oxygen vacancy concentration on the bottom x-axis and fluence on the top x-axis. The resistance begins to gradually increase between a calculated oxygen vacancy concentration of 10^{19} cm^{-3} to 10^{20} cm^{-3} (a fluence of 10^{10} cm^{-2} to 10^{11} cm^{-2}) before abruptly decreasing by almost an order of magnitude. Resistance then gradually increases again before another abrupt decrease. Resistance did not decrease to levels in the on-state range though. This trend was seen repeatedly for TiO_2 devices. After irradiation the device was set and reset twice and the off-state resistance decreased from 7.5 kΩ to 1.5 kΩ, an instability not seen in the TaO_x devices.

Fig. 6 plots resistance versus calculated oxygen vacancy concentration and fluence for another TiO_2 device. During the first two runs the resistance increased slightly near a fluence of 10^{11} cm^{-2} and then decreased. After run two, the device was set and reset multiple times. Initially, the device reset to 15 kΩ, similar to the off-state resistances for the first two runs seen in Fig. 6. After being set and reset five additional times, the off-state resistance had degraded to 750 Ω. The reset current was then increased from -3 mA to -4 mA, resulting in a larger off-state resistance of 30 kΩ for runs three and four. Run three showed a slight increase and then decrease in resistance, similar to the first two runs. During run four the resistance decreased significantly for similar fluence levels. After the final run the device was set and reset five times. The resistance did not show the monotonic degradation seen previously, but the off-state resistance was highly variable, ranging from 10 kΩ to 200 kΩ.

28 MeV Si Ions

The radiation response of a TiO_2 memristor irradiated with 28 MeV Si ions was similar to TaO_x devices, showing evidence of ionization effects. Fig. 7(a) plots resistance versus rad(Si) per shot and Fig. 7(b) plots resistance versus total dose for each run. Similar to the TaO_x devices, the resistance does not change gradually and the device changes resistance once a critical dose per shot is reached, which appears to be roughly 300 Mrad(Si) per shot for the first four runs. The final run does show a change at 150 Mrad(Si) per shot, but it is unclear whether this is a change in the threshold or device variability. Despite this change, the dose per shot threshold is more consistent that the total dose per

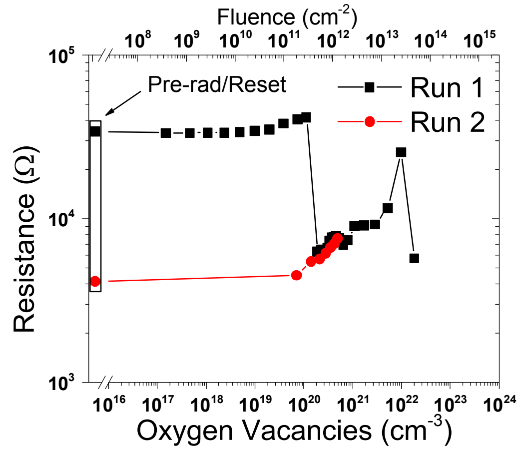

Fig. 5. Resistance versus average oxygen vacancy concentration for a TiO_2 memristor irradiated with 800 keV Ta ions. The part was reset normally between run one and two [15].

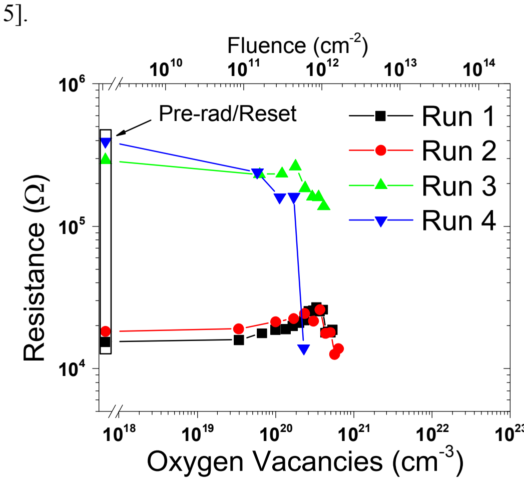

Fig. 6. Resistance versus average oxygen vacancy concentration for a TiO_2 memristor irradiated with 800 keV Ta ions. The part was reset between each run. Between run two and three the part was reset five times and the off-state resistance gradually degraded. The reset current was increased from -3 mA to -4 mA for runs three and four [15].

run, which ranges from 150 Mrad(Si) to 1 Grad(Si). The resistance to which the device switches is also less consistent compared to the TaO_x devices.

5. Discussion

The critical dose per shot required to change the resistance of TaO_x and TiO_2 memristors was calculated to be 60 Mrad(Si) or higher using SRIM. This is significantly higher than what has been required for several space vehicles and payloads [16] and what is considered significant radiation requirements (>100 krad(Si)) [17] and rad-hard from a total dose perspective (100-1000 krad(Si)) [18]. However, the dose required to change resistance may be different for X-ray irradiation due to potential differences such as charge yield. Previous 10 keV X-ray experiments showed TaO_x

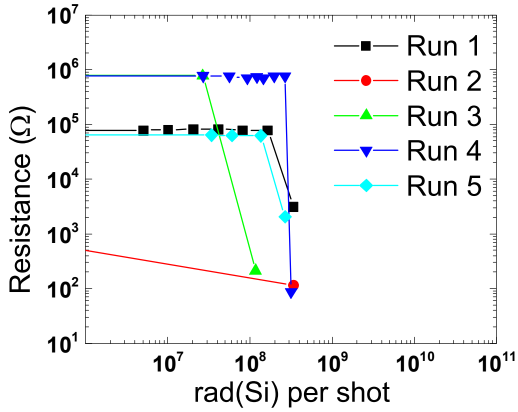

Fig. 7(a). Resistance vs. rad(Si) per shot for a TiO_2 memristor irradiated with 28 MeV Si ions. The part was reset between runs. Duplicate shots are omitted for a given run. The dose per shot threshold appears to be roughly 300 Mrad(Si), although one resistance change occurred at 150 Mrad(Si) [15].

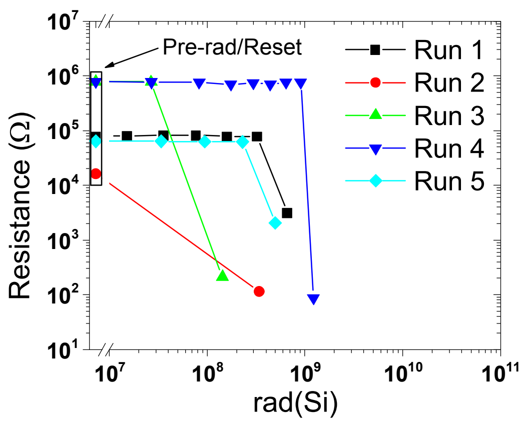

Fig. 7(b). Resistance vs. rad(Si) for a TiO_2 memristor irradiated with 28 MeV Si ions. The part was reset between runs. The dose is cumulative for a given run. There is not a clear total dose threshold [15].

memristors changing resistance states at doses as low as 10 krad(Si), although Co^{60} irradiation up to a dose of 500 krad(Si) did not significantly affect them [9].

TaO_x memristors and a TiO_2 memristor exposed to 10 keV X-ray irradiation in this study showed little change in resistance. Devices one and four are from the same TaO_x wafer as the devices irradiated with heavy ions, while devices two and three are from a different TaO_x wafer. Device five is from the same TiO_2 wafer as the devices irradiated with heavy ions. Devices were irradiated after being switched into either the off-state or the on-state and a read sweep was applied after each irradiation to determine the resistance. During some irradiations, all pins were grounded together. For other irradiations, the parts were left floating. While these parts may not necessarily be floating

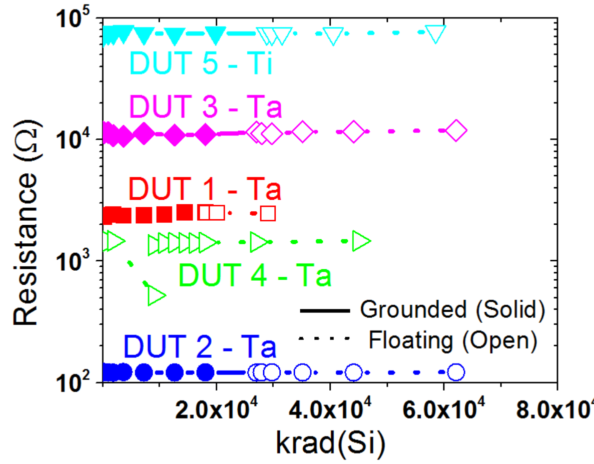

Fig. 8. Resistance versus krad(Si) for four TaO_x parts and one TiO_2 part. DUT 4 was set to the on-state prior to irradiation. All other parts were set to the off-state. Solid lines indicate pins were grounded, dotted lines indicate pins were floating. Read measurements were taken at every point. The highest dose per step was 9 Mrad(Si) for DUT 1 and 18 Mrad(Si) for DUTs 2-4 [15].

in applications, these tests were performed to see whether either setup is more vulnerable to charge buildup. The dose rate was 6000 rad(Si)/s. Fig. 8 plots the resistance versus dose for several TaO_x memristors and a TiO_2 memristor. Each was irradiated under both grounded and floating conditions (except DUT 4, which was only irradiated in the floating condition). Based on ionization data from 28 MeV Si irradiations, applying a read sweep mitigates the effects of ionization, so an increasingly higher dose per step was used. Three of the TaO_x devices shown are in the off-state, while DUT 2 is in the on-state. DUT 5, the TiO_2 device, is in the off-state. DUT 4, one of the TaO_x devices, is the only device that showed any change in resistance during irradiation. The dose of the step that caused this resistance change is 7.2 Mrad(Si). The part did not fully switch to the on-state and reset back to its original resistance without incident. Further irradiations up to a dose of 18 Mrad(Si) at a time did not cause any further changes. Two additional TaO_x devices (not shown) were also irradiated with single step doses of up to 18 Mrad(Si) and showed no changes in resistance.

Aside from one partial switch that was not repeatable, there was no effect from 10 keV X-ray irradiation up to doses of 18 Mrad(Si) per step and total doses of up to 63 Mrad(Si). Although the relationship between the calculated dose for the 28 MeV Si results and the dose for the 10 keV X-ray results is unknown, given the extremely high dose calculations from the 28 MeV Si data, the lack of response to 10 keV X-rays is not surprising. Further work is needed to more fully explore the potential differences between floating and grounded irradiations. The X-ray results in this work do not show the sensitivity seen in [9]. There were

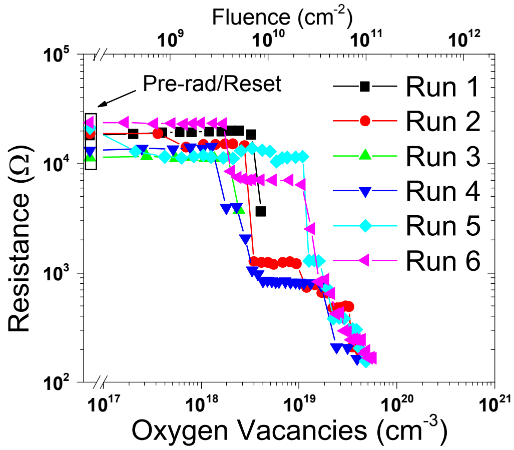

Fig. 9. Resistance versus average oxygen vacancy concentration for a TaO_x memristor irradiated with 800 keV Ta ions. The part was reset between each run. The device was reset ten times after run four and twenty times after run five [15].

some differences between these experiments. While the device structure and packaging were the same, the devices irradiated in [9] were from an older manufacturing batch and device quality may have been improved. Cable connections were shielded to reduce potential noise in this work. An Agilent 4145B was used for X-ray data collection in [9] and a 4156C was used in this work.

The percolation model for oxide breakdown [19], [20] has been used as a framework for modeling resistive switching [21]. TaO_x devices fall into the valence change mechanism class of memristors, and switching can be understood in terms of oxygen vacancies either forming a conductive pathway or dispersing to rupture a conductive pathway. Displacement damage is believed to affect memristor resistance through the creation of oxygen vacancies, which modulate the conductivity of the oxide layer [7]-[9]. Resistance likely begins to change when enough oxygen vacancies have been created near enough to each other to form a pathway that completes the conduction channel.

Resetting a TaO_x memristor with degraded resistance after irradiation restores much of its original off-state resistance, as seen in Figs. 2 and 4, and the devices tested so far remain functional after irradiation. However, there appears to be some cumulative damage from the irradiation. The off-state resistance tends to decrease after each irradiation, which can be seen in Figs 2 and 4. Subsequent irradiations in Fig. 2 show resistance degrading at earlier fluences and in larger increments. If not all of the oxygen vacancies that are created are removed through oxidation or diffusion then it may be easier to create a percolation path of defects during subsequent irradiations.

Resetting a device multiple times may gradually return the conduction channel region closer to its original state. Fig. 9 plots resistance versus calculated oxygen vacancy concentration for a TaO_x memristor irradiated with 800 keV Ta ions. The first four runs show similar trends of resistance degradation at lower fluences as the number of runs increases. After run four, the device was reset ten times. Subsequently, the fluence required for the onset of degradation is seven times higher than the previous run. After run five, the device was reset twenty times. The initial resistance of the device then doubled from the previous run. There was an initial drop in resistance at lower fluences, but all of the remaining degradation occurred at the same fluence as run five, seven times higher than the runs before them.

TiO_2 memristors also belong to the valence change mechanism class of memristors and are often considered similar to TaO_x memristors, but their response to displacement damage is significantly different. Instead of a gradual degradation of resistance with increasing fluence, resistance gradually increases and occasionally drops. The fluence required to cause a drop in resistance varied from part to part and even on different runs on the same part. Some devices show decreasing resistance during repeated cycling after irradiation. The only change observed in post-rad behavior for TaO_x devices is a gradual recovery of resistance discussed in the preceding paragraph. The reason for the difference in radiation responses between TaO_x and TiO_2 memristors is unclear at this point. It may be due to differences in the chemical bonding in the materials or differences in the size and shape of the channel region and the ensuing changes that radiation causes. TiO_2 devices appear to be more resistant to large resistance changes caused by displacement damage initially, but are more prone to having degraded reliability in post-radiation behavior. Radiation may simply be exacerbating a difference between the material system as tantalum based devices have shown some of the highest endurance [22], or it may be due to a difference in switching mechanisms, or a combination of factors.

6. Summary and Conclusions

Our results indicate that there are differences in the radiation response of TaO_x and TiO_2 memristors. However, both types appear to be tolerant to very high levels of radiation before device characteristics are affected, in excess of those required for most rad-hard non-volatile memory space applications. It appears that both materials have a critical ionizing dose threshold between read operations below which they are insensitive to radiation and beyond which resistance changes significantly. Applying small read before this threshold is reached appears to prevent these changes, possibly by draining accumulated charge. This realization may be useful for rad-hard implementation as read voltages can be applied periodically, potentially making the devices practically insensitive to total ionizing dose effects. Devices do not show changes in resistance due to displacement damage from fluences of 10^{10} cm^{-2} or below for 800 keV Ta ions or fluences of 10^{11} cm^{-2} or below for 28 MeV Si ions. Ionizing doses of up to 18 Mrad(Si) per step from 10 keV X-rays did not consistently change resistances. Ionizing doses in the range of 60 Mrad(Si) to 1 Grad(Si) were required to change the resistance of devices exposed to 28 MeV Si ions and applying small voltages and current may mitigate vulnerability to ionization damage.

The behavior of the TaO_x devices irradiated with 800 keV Ta ions appears more consistent and stable after irradiation compared to the post-irradiation off-state resistance degradation seen in the TiO_2 devices irradiated with 800 keV Ta ions in this work, though further investigation on a larger number of devices would be useful. Additionally, TaO_x devices show the potential to recover degraded resistance due to displacement damage with repeated cycles. Further investigation is required to identify and understand the different mechanisms responsible for the degradation in these materials. Regardless, device characteristics appear unchanged for both materials at high total doses and fluences and show great promise for use in radiation-hardened non-volatile memory applications.

ACKNOWLEDGMENTS

The authors would like to thank Kathy Myers (Sandia) for packaging and bonding the devices used in this study and Dan Buller for running the accelerator at Sandia's Ion Beam Laboratory. We would also like to thank R. Schrimpf (Vanderbilt), J. Stanley (Sandia), S. Swanson (Sandia), and M. Van Heukelom (Sandia) for useful discussions.

REFERENCES

[1] J. Hutchby and M. Garner, "Assessment of the Potential & Maturity of Selected Emerging Research Memory Technologies Workshop & ERD/ERM Working Group Meeting," July 2010.

[2] M. J. Marinella, "The future of memory," at 2013 Aerospace Conf., Big Sky, MT, Mar. 2013.

[3] P. R. Mickel, A. J. Lohn, B. J. Choi, J. J. Yang, M.-N. Zhang, M. J. Marinella, C. D. James, and R. S. Williams, "A physical model of switching dynamics in tantalum oxide memristive devices," *Appl. Phys. Lett.*, **102**, 223502 (2013).

[4] F. Miao, J. P. Strachan, J. J. Yang, M.-X. Zhang, I. Goldfarb, A. C. Torrezan, P. Eschbach, R. D. Kelley, G. Medeiros-Ribeiro, and R. S. Williams, "Anatomy of a nanoscale conduction channel reveals the mechanism of a high-performance memristor," *Adv. Mater.* **2011**, 23, pp. 5633-5640.

[5] J. J. Yang, D. B. Strukov, and D. R. Stewart, "Memristive devices for computing," *Nature Nanotechnology.*, **8**, 13-24 (2013).

[6] W. M. Tong, J. J. Yang, P. J. Kuekes, D. R. Stewart, R. S. Williams, E. DeIonno, E. E. King, S. C. Witczak, M. D. Looper, and J. V. Osborn, "Radiation hardness of TiO_2 memristive junctions," *IEEE Trans. Nucl. Sci.*, vol. 57, pp. 1640-1643, June 2010.

[7] H. J. Barnaby, S. Malley, M. Land, S. Charnicki, A. Kathuria, B. Wilkens, E. DeIonno, and W. M. Tong, "Impact of alpha particles on the electrical characteristics of TiO_2 memristors," *IEEE Trans. Nucl. Sci.*, vol. 58, pp. 2838-2844, Dec. 2011.

[8] E. DeIonno, M. D. Looper, J. V. Osborn, and J. W. Palko, "Displacement damage in TiO_2 memristor devices," *IEEE Trans. Nucl. Sci.*, vol. 60, no. 2, pp. 1379-1383, Apr. 2013.

[9] M. J. Marinella, S. M. Dalton, P. R. Mickel, P. E. 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, pp. 2987-2994, Dec. 2012.

[10] Y. Wang, H. Lv, W. Wang, Q. Liu, S. Long, Q. Wang, Z. Huo, S. Zhang, Y. Li, Q. Zuo, W. Lian, J. Yang, and M. Liu, "Highly stable radiation-hardened resistive-switching memory," *Elec. Dev. Lett.*, vol. 31, no. 12, pp. 1470-1472, Dec. 2010.

[11] X. He, W. Wang, B. Butcher, S. Tanachutiwat, and R. E. Geer, "Superior TID hardness in TiN/HfO_2/TiN ReRAMs after proton radiation," *IEEE Trans. Nucl. Sci.*, vol. 59, no. 5, pp. 2550-2555, Oct. 2012.

[12] D. Lee, J. Lee, S. Jung, S. Kim, J. Park, K. P. Biju, M. Choe, T. Lee, H. Hwang, "Proton irradiation effects on resistive random access memory with ZrO_x/HfO_x stacks," *IEEE Trans. Nucl. Sci.*, vol. 58, no. 6, pp. 3317-3320, Dec. 2011.

[13] J. J. Yang, M.X. Zhang, J. P. Strachan, F. Miao1, M. D. Pickett, R. D. Kelley, G. Medeiros-Ribeiro, and R.S. Williams, "High switching endurance in TaOx memristive devices," *Appl. Phys. Lett.*, **97**, 232102 (2010).

[14] J. F. Ziegler, SRIM-2012 [Online]. Available: www.srim.org

[15] 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.*, accepted for publication, vol. 60, no. 6, Dec. 2013.

[16] M. R. Shaneyfelt, P. S. Winokur, T. L. Meisenheimer, F. W. Sexton, S. B. Roeske, M. G. Knoll, "Hardness variability in commercial technologies," *IEEE Trans. Nucl. Sci.*, vol. 41, no. 6, pp. 2536-2543, Dec. 1994.

[17] P. S. Winokur, G. K. Lum, M. R. Shaneyfelt, F. W. Sexton, G. L. Hash, and L. Scott, "Use of COTS microelectronics in radiation environments," *IEEE Trans. Nucl. Sci.*, vol. 46, no. 6, pp. 1494-1503, Dec. 1999.

[18] G. L. Hash, M. R. Shaneyfelt, F. W. Sexton, and P. S. Winokur, "Radiation hardness assurance categories for COTS technologies," at 1997 Radiation Effects Data Workshop, pp. 35-40, July 1997.

[19] R. Degraeve, G. Groeseneken, R. Bellens, J. L. Ogier, M. Depas, P. J. Roussel, and H. E. Maes, "A consistent model for the thickness dependence of intrinsic breakdown in ultra-thin oxides," Tech. Dig. Int. Electron Devices Meet. Pp. 863-866 (1995).

[20] J. H. Stathis, "Percolation models for gate oxide breakdown," J. Appl. Phys. 86, pp. 5757-5766 (1999).

[21] S. Long, C. Cagli, D. Ielmini, M. Liu, and Jordi Sune, "Analysis and modeling of resistive switching statistics," J. Appl. Phys. 111, 074508 (2012).

[22] M. J. Lee, C. B. Lee, D. Lee, S. R. Lee, M. C. Ji, 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, pp. 625-630, July 2011.

BIOGRAPHIES

Coming Soon