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NSTRF FINAL REPORT NASA Grant Number (NNX14AL69H) 11/26/2018 Resistive memory for radiation resistant non-volatile memory University at Albany / SUNY Polytechnic Institute	
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NASA Research Collaborator	Jean Yang-Scharlotta Jet Propulsion Laboratory

1. EXECUTIVE SUMMARY:

As space programs increase in number and scope, there is an increasing need for radiation-hardened electronic devices and circuits. In particular, missions to high-radiation environments, such as Europa, would greatly benefit from improved radiation hardness in electronic devices. In pursuit of this goal, resistive memory (RRAM) devices were fabricated at SUNY Polytechnic Institute and evaluated for radiation hardness. Our objectives were to produce RRAM devices resistant to high levels of radiation damage and to demonstrate that these devices would improve mission lifetime in high-radiation environments. Furthermore, the underlying mechanisms of radiation were investigated to provide recommendations for radiation-hardening RRAM devices, which could be applied to any candidate RRAM devices being considered for space applications.

Devices were fabricated using several fabrication approaches, including patterning by shadow mask, photolithography-based etching, and photolithography-based liftoff. In each of these cases, total ionizing dose (TID) effects and displacement damage dose (DDD) effects were measured. TID effects from exposure to a ^{60}Co gamma source were not observed to cause changes in device resistance or switching parameters in any experiments, with each device tested to at least 20 Mrad(Si). DDD was measured as radiation-generated oxygen vacancies per cm^3 since oxygen vacancies are generally considered to be the active species involved in switching these devices. The lowest DDD level that caused a device to change resistance state was 10^{21} vacancies per cm^3, and most devices failed at 10^{22} vacancies per cm^3. This is an extremely high DDD level, even for RRAM devices, which have been reported to fail in the range of 10^{17}-10^{20} vacancies per cm^3. For comparison, an example flash memory device failed at 10^{15} vacancies per cm^3. Vendor-fabricated devices with a similar composition to our own were also tested against TID and DDD. The vendor-fabricated devices did not exhibit changes due to TID, up to the tested level of 30 Mrad(Si). Meanwhile, vendor devices exhibited resistance state changes at 10^{21} vacancies per cm^3, similar to our own devices. These results indicate that TaO_x-based RRAM devices may be particularly resilient to both TID and DDD effects.

The very high tolerance to radiation effects is most likely due to the high intrinsic concentration of oxygen vacancies within our devices. Based on X-ray photoelectron spectroscopy (XPS) measurements, there are approximately 10^{22} oxygen vacancies per cm^3 in our devices as deposited. Most devices failed when the radiation-induced vacancies reached this level, indicating suggesting that a high intrinsic vacancy concentration protects against lower levels of displacement damage.

High vacancy concentration likely also protects against TID by facilitating leakage of trapped charge out of the oxide. The use of a thin switching oxide (25 nm TaO_x for our devices) is also expected to improve radiation hardness, as there is less room for charge trapping. Therefore, those wishing to produce very radiation-tolerant RRAM devices can probably achieve this by using a thin oxide that contains a high intrinsic concentration of oxygen vacancies.

Our devices appear to be very tolerant of radiation effects, and would greatly increase the expected lifetime of a mission to Europa or another high-radiation target compared to flash memory devices. The similar radiation performance of vendor-fabricated devices is promising for adoption of RRAM devices as radiation-hardened memory devices for use in space. With continued commercial development of these devices, RRAM devices are strong candidates for next-generation memories that are inherently rad-hard.

Note: These experiments were carried out in collaboration with the NASA Jet Propulsion Laboratory and Sandia National Laboratory. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

U.S. DEPARTMENT OF ENERGY   Sandia National Laboratories

2. **NOTABLE ACCOMPLISHMENTS**: Provide a list of your notable accomplishments over the course of the fellowship award (please provide state-of-the-art context).

- Produced several generations of TaO_x-based RRAM devices using an evolving device fabrication process. TaO_x was chosen based on several reports of TaO_x-based devices with excellent switching properties. Although our fabrication processes were not novel, they enabled radiation experiments on a family of similar devices.
- Devices were very tolerant of TID effects, with no failures observed in any TID tests. TID tests with ^{60}Co gamma radiation reached levels of 20 Mrad(Si) up to 70 Mrad(Si). By comparison, some RRAM devices fail at 1-5 Mrad(Si), while some others exhibit no device failures at 10, 20, or even 60 Mrad(Si). Heavy ion bombardment led to TID levels on the order of 1 Grad(Si), which also did not affect the devices. One previous study of HfO_x devices observed no changes at 5 Grad(Si) from similar ion beam experiments. Our devices appear to be very tolerant of TID effects, even compared to other RRAM devices, and they easily exceed the 1 Mrad(Si) requirement of NASA's X2000 program for a visit to Europa.
- Our devices were also very tolerant of DDD effects. The lowest DDD level which resulted in a change of resistance state was 10^{21} radiation-induced oxygen vacancies per cm^3. By comparison, other RRAM devices typically fail in the range of 10^{17}-10^{20} vacancies per cm^3. An example flash memory device reportedly failed at 10^{15} vacancies per cm^3, 6 orders of magnitude below our RRAM devices. Our devices generally failed once the radiation-induced vacancy concentration surpassed the very high intrinsic vacancy concentration, suggesting that a high intrinsic level of vacancies could make these devices more resilient to DDD effects. At the DDD level required for even one of our devices to fail, ~2% of atoms were displaced within the films. If these levels were ever reached in a real application, peripheral circuitry would likely fail first.

- Vendor-fabricated devices with a similar composition to our own devices were tested for TID and DDD effects. The vendor devices did not exhibit any TID-induced changes up to the tested level of 30 Mrad(Si). Vendor devices exhibited a change in resistance state due to DDD effects at 10^{21} vacancies per cm^3, similar to our own devices. This could indicate that TaO_x-based devices in general are more tolerant to DDD effects than devices made with other materials. This effect could be due to the relatively high mobility of oxygen vacancies in Ta_2O_5, facilitating defect migration and recombination.
- A Fermi estimate indicated that our devices would survive indefinitely in low Earth orbit, and at least several years at Europa, before radiation-induced device failure. Even then, most radiation-induced failures were soft errors, indicating the possibility for device recovery after a failure.
- The studies described here were published in two separate conference proceedings. Final experiments are expected to be published in a journal, pending approval of each collaborating institution.

3. **MAJOR MEETINGS ATTENDED**: Provide a list of major meetings or conferences you attended over the course of the fellowship award.

   - International Integrated Reliability Workshop 2015 - (Holt, Yang-Scharlotta, and Cady, 2015)
   - Materials Research Society (MRS) Spring 2017 - (Holt et al., 2017)
   - Albany Nanotechnology Symposium (ANTS) 2018

4. **HONORS/AWARDS RECEIVED**: Provide a list of honors/awards you received over the course of the fellowship award.

   N/A

5. **PATENT(S), LICENSE(S) OR AGREEMENT(S)**: Provide any patent(s), license(s) or agreement(s) that resulted from this award (please discuss this with your advisor, if needed).

   A non-disclosure agreement (NDA) was implemented between JPL, Sandia National Laboratory, and SUNY to protect vendor confidentiality during vendor device testing.

6. **SUMMARY OF INTERACTION WITH NASA**: Provide a summary of your interactions with NASA over the course of the fellowship award.

   - Experiments were designed and carried out in close collaboration with our NASA mentor, Jean Yang-Scharlotta
   - A visiting technologist experience (VTE) was conducted at the Jet Propulsion Laboratory (JPL) in summer 2015 for TID experiments on our RRAM devices. These results were presented at the IIRW 2015 meeting.
   - A short VTE was conducted at JPL in April 2016 for initial electrical and TID tests on the vendor devices.

- A third VTE was conducted at JPL in November 2017 for TID tests on devices fabricated using an optimized photolithography-based fabrication approach. Additional TID experiments on the vendor devices were carried out during this VTE.
- In each of the VTE's listed above, experiments were conducted in collaboration with the radiation effects team at JPL.

7. **DEGREE GRANTED**: Provide the degree granted, field of study and date received (or anticipated date); an exact date is needed (i.e., mm/dd/yyyy).

   Ph.D. in Nanoscale Engineering (Expected 12/01/2018)

8. **EMPLOYMENT**: Provide employer, location, job title, job responsibilities, etc. or other post-fellowship plans, including contact information (contact information is optional).

   Continuing to assist with research as a senior graduate student or postdoc while searching for a job in semiconductors or aerospace.
   Contact: jholt@sunypoly.edu
   Alternate contact: ncady@sunypoly.edu

9. **OTHER PERTINENT INFORMATION**: Provide any other pertinent information *including feedback to the Program on lessons learned*.

   N/A