OVERVIEW OF RADIATION EFFECTS ON EMERGING NON-VOLATILE MEMORY TECHNOLOGIES

by

Irfan S. FETAHOVIĆ [1*], ***Edin Ć. DOLIĆANIN*** [1], ***Djordje R. LAZAREVIĆ*** [2], ***and Boris B. LONČAR*** [3]

[1]State University of Novi Pazar, Novi Pazar, Serbia
[2] Vinča Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[3] Faculty of Technology and Metallurgy, University of Belgrade, Belgrade, Serbia

Technical paper
http://doi.org/10.2298/NTRP1704381F

In this paper we give an overview of radiation effects in emergent, non-volatile memory technologies. Investigations into radiation hardness of resistive random access memory, ferroelectric random access memory, magneto-resistive random access memory, and phase change memory are presented in cases where these memory devices were subjected to different types of radiation. The obtained results proved high radiation tolerance of studied devices making them good candidates for application in radiation-intensive environments.

Key words: *non-volatile memory, radiation effect, resistive RAM, ferroelectric RAM, magneto-resistive RAM, phase change memory*

INTRODUCTION

The memory system serves as the entity for information (data) storage in a computer system. DRAM and SRAM represent volatile memories since they lose their content if the supply voltage is turned off. Non-volatile memories, on the other hand, retain their information even when they are powered off. There are a variety of non-volatile memories; some of them are read-only, while some can be written to as well as read. EPROM and EEPROM are well known, old non-volatile memory technologies. Flash memory is a type of non-volatile memory, based on EEPROM, that has become an important conventional storage technology.

All above-mentioned memory technologies represent charge memories. They require discrete amounts of charge to induce a voltage, which is detected during reads. In contrast, resistive memories use electrical current to induce a change in atomic structure, which impacts the resistance detected during reads. Resistive memories are amenable to scaling because they do not require precise charge placement and control [1]. Resistive random access memory (RRAM), ferroelectric random access memory (FRAM), magneto-resistive random access memory (MRAM), and phase change memory (PCM) represent emergent, resistive, non-volatile memory technologies. While radiation effects in EPROM, EEPROM and Flash memories, their radiation hardness and applicability in harsh environments have been carefully studied and are well known [2, 3], the immunity of resistive non-volatile memory technologies to ionizing radiation remains an important research topic yet to be fully explored.

In this paper we will give an overview of current research into radiation effects in emergent, non-volatile memory technologies.

* Corresponding author; e-mail: ifetahovic@np.ac.rs

RESISTIVE RANDOM ACCESS MEMORY

When a large voltage is applied to insulators such as metal oxides their resistance changes. This phenomenon is called resistive switching and was first reported in 1960. Samsung was the first to develop RRAM array integrated CMOS technology in 2004. Following this success, extensive research activities were conducted to demonstrate resisting switching behavior in various binary oxides such as NiO, TiO_x, CuO_x, ZrO_x, ZnO_x, HfO_x, TaO_x, AlO_x, *etc*., since these materials are compatible with the CMOS fabrication process. Generally speaking, there are two types of RRAM: oxide-based RRAM and conductive-bridging RAM. The first type is based on conductive filaments consisting of oxygen vacancies, while the second type is based on conductive filaments consisting of metal atoms [4]. In this overview we will focus on the first type: oxide-based RRAM.

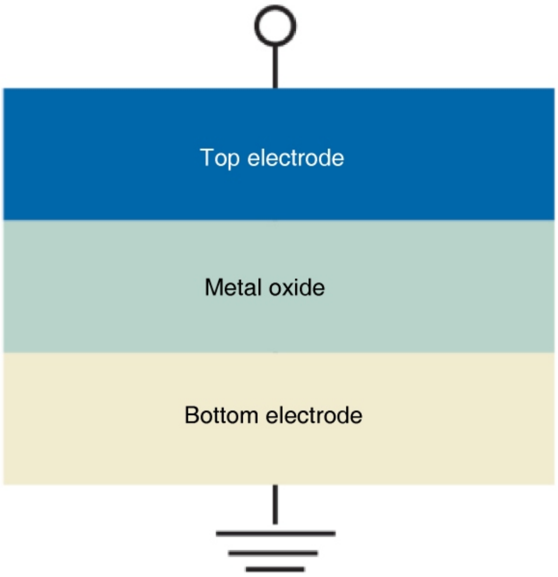

Figure 1. RRAM device structure

The typical device structure of RRAM is depicted in fig. 1. It is a sandwich-like structure where a thin oxide layer is placed between two electrodes. The materials used for electrodes are metals or conductive nitrides. The device can be in two distinct states: high resistance state (HRS) and low resistance state (LRS), used to represent the logical „0" and „1", respectively. Switching from HRS to LRS is called the „set" process, while switching from LRS to HRS is called the „reset" process.

Some authors consider the initial resistance state as distinct and call it virgin state. Usually, for the fresh samples in its initial resistance state, a voltage larger than the set voltage is needed to trigger the resistive switching behaviors for the subsequent cycles [5]. This is called the „electroforming" or „forming" process. Although the switching mechanism and classification are not clear, broadly, there are two kinds of switching polarity: unipolar and bipolar. Unipolar switching means that the same voltage polarity is applied for forming, set and reset, but with a different amplitude. In bipolar switching, the switching direction is dependent on both amplitude and polarization of the applied voltage. The reading content from the RRAM memory cell is performed by applying a small voltage to detect whether the cell is in HRS or LRS. In early stages of RRAM research and development there have been many deficiencies such as: large device area long programming time, low endurance and large forming voltage. Today, many of these deficiencies have been overcome by technological improvements. The industry has already managed to build RRAM chips with peripheral circuitry and capacity ranging from 4 Mb to 32 Gb, indicating a bright future for RRAM as a non-volatile memory technology for practical applications. In the next section we will present current research results in testing radiation resistance of RRAM memory devices.

Numerous researches have demonstrated advantages of the $TiN/HfO_x/Pt$ RRAM device structure in terms of switching speed, low switching voltage, endurance, data retention, *etc*. Total ionization dose (TID) effects of gamma ray irradiation were studied in [6]. ^{60}Co was used as the γ-ray source for the study and the device under test (DUT) were exposed to radiation at the rate of 100 rad* (Si)s^{-1}, with the total dose up to 1 Mrad(Si). Before irradiation, 10 RRAM devices were programmed to the high resistance state, while another 10 devices were programmed to the low resistance state. The changes in switching behavior, static resistance and memory performance of the irradiated devices as a result of gamma irradiation were investigated. It was shown that the switching mechanism and memory performance are slightly affected, in various degrees, due to the irradiation-induced oxygen vacancies and holes. It was concluded the $TiN/HfO_x/Pt$ RRAM device has a stable memory performance and a good radiation resistivity to γ-ray irradiation.

Heavy ion radiation effects on $TiN/HfO_2/W$ RRAM devices were studied in [7]. The experiments were carried out with a variety of ions, including He, N, Ne, and Ar, at ion fluencies ranging from 10^{12} to 10^{15} cm^{-2}. Functional failures were not observed in most devices following irradiation. For ion fluencies from 10^{12} cm^{-2} up to 10^{14} cm^{-2}, there was little change in switching properties of the irradiated RRAM devices. However, in most RRAM devices beyond a fluence of 10^{14} cm^{-2} it was noted static resistance decreases with heavier ions. Ne and Ar irradiation at ion fluence of 10^{15} cm^{-2} caused spontaneous switching from high resistance state to low resistance state (bit flips) in all DUT. Although switching and forming mechanisms in metal oxide RRAM are still not well understood, there are several models trying to explain the phenomenon. However, the most famous model of the forming process is based on trap-assisted tunneling (TAT). As the TAT current increases, Hf-rich ohmic conducting filament (CF) is formed. The voltage-induced formation or rupture of the conduction filament (CF), which is formed as a consequence of TAT current increase, comprises the on/off switching of the RRAM device. Based on theoretical analysis and previous research, the authors asserted that the radiation creates oxygen vacancies which induce electron trapping in HfO_2. Namely, heavy-ion radiation causes an increase in oxygen vacancy concentration in the HfO_2 layer which reduces the trap-to-trap distance and thus lowers the static R_{off}. Moreover, the high density of radiation induced oxygen vacancies may cause the formation of percolation path(s) between the CF tip and the electrode, leading to the changes between two resistance states.

Wang Y., *et al*. analyzed TID γ-radiation effects on Cu-doped HfO_2-based RRAM devices [8]. The

* 1 rad = 10^{-2} Gy

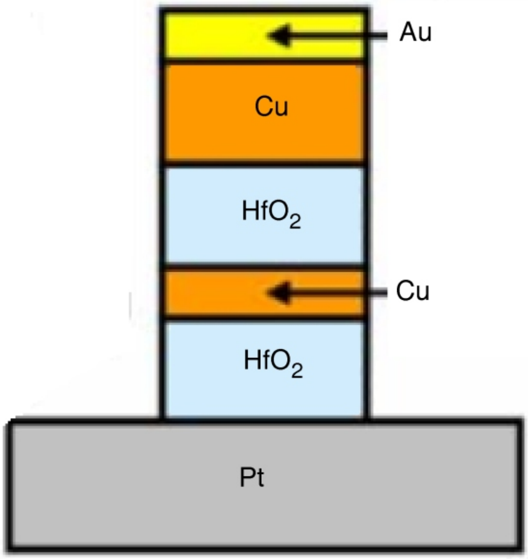

Figure 2. Cu-doped H_fO_2-based RRAM device structure

schematic of the tested devices is shown in fig. 2. The authors used a ^{60}Co γ-ray source with a total dose as high as 3.6 10^5 rad (Si). Basic RRAM parameters such as I-V characteristics, resistance of high resistance state (R_{HRS}), resistance of low resistance state (R_{LRS}), transition voltage of the set process (V_{set}), transition voltage of the reset process (V_{reset}), were observed before and after irradiation. Radiation effects on the above mentioned parameters were tested on 30 samples using a statistical approach. The distribution of V_{reset} and R_{LRS} showed no significant change before and after irradiation. Mean values of V_{set} were different prior and after irradiation, but maximum values of V_{set} after irradiation didn't change significantly. Therefore, successful write operations were still maintained since the maximum transition voltage value is important in terms of correct programming. The mean value of R_{HRS} decreased three times after irradiation, but was still in order of 10^8 . It was noted that operation speed and endurance experienced nearly no degradation after irradiation. To conclude, Cu-doped HfO_2 devices showed highly stable characteristics and superior radiation resistance, thereby demonstrating a great potential for aerospace and nuclear applications.

Radiation effects on tantalum oxide-based RRAM devices were investigated in [9]. The DUT were exposed to gamma radiation and proton bombardment. Gamma radiation experiments were carried out using a Co^{60} gamma source to a dose of 64.7 Mrad(Si) at a rate of 38 rads^{-1}. The authors did not investigate resistance shifts or bit flips due to irradiation, but resistance levels during switching and switching voltages. The devices appeared to be resistant to the effects of gamma radiation. The same voltage was required for the irradiated and control group devices. Furthermore, resistance levels of the irradiated group were between the two control groups, while statistical analysis showed no significant differences with a 99 % confidence. Likewise, ionic radiation (H, N, Ar$^+$) up to 10^{15} ionscm^{-2} did not cause any significant effects. The greatest observed difference was in the ratio R_{off}/R_{on} after nitrogen radiation exposure (from 3 to 8). Since the previous research confirmed that transitions from HRS to LRS were a common effect of radiation, and R_{off}/R_{on} was expected to decrease due to radiation, the conclusion of the authors was to dismiss increases in R_{off}/R_{on} as normal device variations.

Compared to other RRAM technologies, transitional metaloxide-based bipolar devices, *e. g.* TaO_x-based RRAM devices, show better behaviors in terms of switching speed, thermal stability, and cycling performance. However, a small band gap and presence of many defects in the oxide makes them more vulnerable to radiation, thus systematic investigation of TID effects is necessary to estimate the radiation tolerance and applicability of these devices in a harsh environment. TID effects of γ-rays generated from a ^{60}Co source on the TaO_x-based RRAM were studied in [10]. TaO_x-based RRAM devices with different parameters such as oxide thicknesses, size and HRS were irradiated by γ-rays to investigate the influence of these parameters on the response of RRAM devices to radiation. The LRS of the RRAM was immune to TID effects, whereas the radiation tolerance of the HRS of RRAM depended on the dimensions of the device, including the thickness of the oxide film and the area of the device. The HRS of the device with a large area and thick oxide layer, particularly the HRS with small R_{HRS}, was found to be vulnerable to TID effects and had a high probability to change into LRS. Compared to the device with a 25-nm-thick oxide, the HRS of devices with a thicker oxide layer (50 nm) suffered larger degradation. Gamma ray irradiation causes electron-hole pair generation; some of them recombine, while others drift or hop under the electric field that is caused by the work function difference between electrodes. The electric field in the thicker oxide film is lower than that in the thinner oxide. In thicker oxide films more holes are trapped in the body of the oxide, while for the thinner oxide more holes are trapped near the interface and easier electron tunneling from electrode may detrap the trapped holes. Thus, the electron path cannot be easily formed in the thinner oxide. As a result, the thinner oxide exhibits better irradiation tolerance.

Resistive switching properties of VCM RRAM devices (TiN/HfO_2/TiN) were investigated after exposure to proton radiation with TID of 1.5, 3, and 5 Grad(Si), and compared to similar measurements from electrochemical metallization memory (ECM) RRAM devices (Pt/HfO_2:Cu/Cu) in [11]. The study pertained only to the resistive device element in a RRAM-based NVM system and not to the system as a whole (*i. e.* CMOS control circuitry). The obtained results showed that VCM-based TiN/HfO_2/TiN RRAM exhibit superior TID hardness compared to ECM-based Pt/HfO_2:Cu/Cu RRAM devices. All VCM-based TiN/HfO_2/TiN devices remained functional after irradiation with negligible degradation; switching parameters such as average V_{set}, V_{reset}, R_{on}, R_{off} showed minimal or no degradation; and, TID radiation enhanced the uniformity of resistive switching among all VCM devices. These results are due to the distinct conduction filament (CF) formation and switching mechanisms in VCM and ECM-based devices. Trap-assisted-tunneling associated with Hf-rich CF formation kinetics appears less sensitive to proton-induced vacancy density compared to the ECM system where proton-induced vacancies inhibit the formation of the Cu conduction filament through internal field reduction due to charge trapping. Thus, the comparison of TID effects suggested that HfO_2-based VCM RRAM were better candidates for application in radiation hardened electronics.

The HfO_2/Hf-based bipolar RRAM technology is one of the most popular candidates in the field of RRAM research. It gained attention due to its good endurance, high speed, low voltage, and compatibility with CMOS integrated circuits. Total-ionizing dose effects on the electrical properties of HfO_2/Hf-based bipolar RRAM devices were investigated in [12]. Although X-ray radiation exposure caused changes in on and off resistance, these are insignificant, at least at levels up to 7 Mrad(SiO_2). X-ray irradiation generates excess carriers in the HfO_2 layer which recombine or are trapped at defect sites in the HfO_2 layer or at interfaces between layers. However, they have no effect on the conductive path of the RRAM devices. When DUT were exposed to 1.8 MeV proton radiation, no deviations from the pre-irradiation state were observed for ion fluencies up to 10^{14} cm^{-2}. When the fluence was higher, there was an increase in current flow through the virgin state device. The authors used TRIM simulations to further explain proton irradiation effects on RRAM devices. The simulations showed that protons generate oxygen vacancies and displacement damage throughout the oxide layer which can form a leakage path in virgin state RRAM, thus lowering the resistance. However, changes in resistance do not affect the state; all LRS devices remain in the LRS and all HRS devices remain in the HRS. The obtained results suggested that HfO_2/Hf -based RRAM devices are good candidates for critical components of radiation-tolerant electronics.

The TID effects of ^{60}Co γ-ray radiation on RRAM devices with the structure of Ag/AlO_x/Pt were studied in [13]. R_{LRS}, V_{set}, V_{reset}, are almost immune to radiation, whereas the initial resistance, R_{HRS} and forming voltage were significantly impacted after radiation due to the radiation-induced holes. The Ag/AlO_x/Pt RRAM devices exhibited radiation immunity to a TID up to 1 Mrad(Si) and are very good candidates for radiation-hardened electronics applications.

Summary

In recent years, RRAM attracted great attention in the research community as a promising memory technology for the future due to its speed, endurance, high compatibility with CMOS devices, low power consumption and high storage density. Radiation resistance of RRAM was carefully tested in numerous experiments to assess potential application of these devices in harsh environments, including application in aerospace and nuclear engineering. Although ionizing radiation causes some changes in electrical properties and switching behavior of RRAM devices, these changes are not significant and they do not deteriorate memory performance. Thus, RRAM is a good candidate for application in radiation- hardened electronics.

FERROELECTRIC RANDOM ACCESS MEMORIES

Ferroelectric random access memories (FRAM) employ a unique type of crystalline dielectric material – a ferroelectric. By definition, ferroelectrics exhibit a spontaneous polarization (a polarization that occurs naturally within the crystal with no applied electric field) that can be switched between more than one stable state by the application of an electric field [14]. A simplified scheme of a FRAM memory cell is shown in fig. 3. FRAM devices utilize the ferroelectric capacitor where two net polarization states can be induced, depending on the applied electric field. The capacitor can be polarized by applying a high electric field; after the field is removed, the polarization state remains, which also defines a memory state. This phenomenon is the basis for the application of ferroelectric material in memory devices. Switching from one stable memory state to another is acquired by using an electric field with the same magnitude but with a direction opposite to that initially applied. This process defines how the data is written and stored in FRAM memory. A FRAM memory is read by detecting the presence of an excess charge pulse that is stored in the capacitor during the process of switching between two polarization states. Due to its low power consumption, dura-

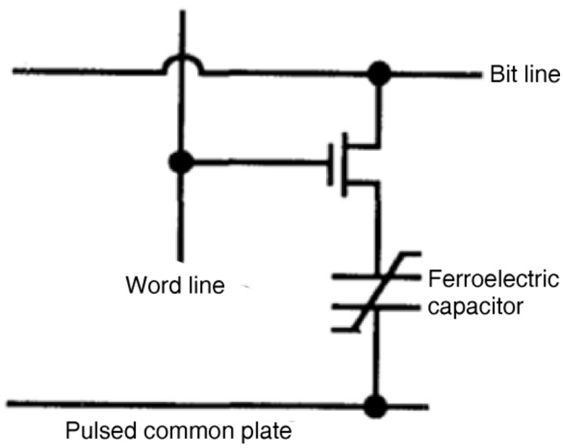

Figure 3. FRAM memory cell

tion, easy embedded design, short read and write times and repeatable ereaseability, FRAM seems to be a good candidate for the non-volatile memory technology of the future.

The TID effects on FRAM memory cells were studied in [15]. The samples were exposed to electron, X-ray and Co-60 γ-ray radiation sources. The testing was done on a 1 Mbit parallel FRAM fabricated in 0.13 m CMOS technology, while a $Pb(Zr_{1-x}Ti_x)O_3$ (PZT) thin film was used for the ferroelectric capacitor. Gamma radiation was performed using a Co-60 γ-ray source. Three memory devices were used; one, denoted as SN1, received a 15 rad(Si)/s dose rate, while the other two (SN2 and SN3) received 50 rad(Si)/s dose rates. Sample SN1devices functioned properly when the deposited dose reached 37.5 krad(Si). Data errors in SN2 and SN3 were observed when the deposited dose reached 100 krad(Si) and 200 krad(Si), respectively. Electron irradiation on two samples (SN4 and SN5) was realized by an electron accelerator with high power and a high dose rate; the dose rate was 2 10^4 rad(Si)/s, and the energy was 1 MeV. During irradiation, the deposited dose reached 3 Mrad(Si). The samples functioned normally when the deposited dose reached 1 Mrad(Si) and 2 Mrad(Si), respectively. Errors (bit flips) occurred in both samples when the dose was 3 Mrad(Si) and the number of errors was approximately several hundred bits. X-ray irradiation was performed on two locations of the FRAM memory sample, the total deposited dose being 3.8 Mrad(SiO_2) and 4.7 Mrad(SiO_2), respectively. Bit flips were observed after 2.8 Mrad(SiO_2) (4.8 Mrad(Si)). After reprogramming, the sample needed 10 minutes at room temperature to restore its functionality. The authors noted the difference between the gamma radiation response of the FRAM memory cell block and full chip. The full chip was more sensitive to gamma radiation because of the technology and circuit characteristics of the peripheral CMOS circuitry. Due to the degradation of the NMOS transistor in series with the ferroelectric capacitor, the failure threshold of FRAM memory cells caused by X-ray and electron irradiation is lower than that of the ferroelectric capacitor.

Gupta *et al*. analyzed the impact of heavy ions on commercial FRAM memories [16]. The DUT was a 4 Mbit asynchronous FRAM manufactured by Cypress Semiconductor (FM22L16) used in 16-bit word mode. Particle fluence varied from 5 10^3 to 1.22 10^7 cm^{-2}. The test samples were analyzed in both static and dynamic mode. Static mode testing means that write or read operations are not performed during irradiation, as opposed to the dynamic mode. For the dynamic tests, the authors employed the March Dynamic Stress algorithm. Static mode tests were conducted with LET ranging from 1.8 up to 64.3 MeV cm^2mg^{-1} and three distinct data patterns (all zeros, all ones, checkerboard pattern). The results showed that radiation sensitivity was not dependent on the data pattern. The relation between FRAM radiation sensitivity and ion fluence was observed; sensitivity at various LET is higher for particle fluence levels above 10^6 cm^{-2}, when compared to lower fluence runs. In summary, the tested FRAM had good heavy ion SEU resilience in the static mode at low levels of fluence. On the other hand, when the fluence was high (even at low LET), errors (and particularly SEU) were detected. The authors concluded that temporary effects may have occurred on the CMOS part of the memory, which was not affected at lower fluence levels, as the ferroelectric part of the memory is immune to SEUs. The results for dynamic mode testing showed no SEL event was detected during the test campaign performed at room temperature (20 °C), up to a LET of 69.3 MeV cm^2mg^{-1}. The number of collected bit errors was higher compared to static mode tests, due to Single Event Transients occurring in the control logic during read/write operations.

Analysis of X-ray and proton radiation effects on commercial Ramtron FM18L08 FRAM chips, as well as the correlation between radiation damage and irradiation temperature and supply voltage, were conducted in [17]. Irradiation tests were performed at different temperatures ranging from –15 °C to 140 °C, when the test devices were both powered and unpowered, and by using 10-keV X-rays and a 5-MeV proton beam. Bit errors were not observed after X-ray irradiation at 85 °C for doses as high as 8 Mrad(Si). However, an increasing number of stuck bits (bit stuck at one state and cannot switch back to the original state, regardless of the new programming value) were observed with increasing irradiation temperature and radiation dose. The comparison between X-ray and proton radiation effects at two different temperatures was conducted in terms of the number of stuck bits. Results showed that FRAM devices are more sensitive to X-ray radiation. The study of recovery from irradiation showed that radiation damage from both X-ray and proton sources progressively annealed after 30 days and the recovery time was reduced if the test devices were subjected to repeated write/read cycles or if a moderately high temperature (up to 200 °C) was introduced. The radiation sensitivity of powered devices was 10 times greater than that of unpowered devices. If the device is powered during X-ray irradiation, write/read errors were not observed for a radiation dose up to 280 krad(Si). After 400 krad(Si), the device suddenly stopped working.

Total ionization dose testing on two different commercial FRAM memory chips (64 Kb Ramtron FM1608 and 256 Kb Ramtron FM1808) was performed in [18]. Two gamma dose rates were used: a high dose rate of 50 rad $(Si)s^{-1}$ and a low dose rate of 0.0116 rad $(Si)s^{-1}$. It was noted that for both device types standby currents increased rapidly after 10 krad(Si). When the dose rate was 50 rad$(Si)s^{-1}$, test devices performed normally at 10 krad(Si), but started having read errors at around 12.5 krad(Si). They stopped to function when the total dose reached 25 krad (Si) and did not recover after 24 hours at the 200 °C annealing process. Results for the low dose rate were similar but showed lower radiation resistance; the devices failed at 20 krad(Si). Four devices of each part type were also irradiated with protons. Standby, read and program currents were recorded between radiation levels. After 15 krad (Si), the standby current increased rapidly. After 25 krad (Si), both devices failed to write data.

The TID sensitivity of the function blocks of the FRAM is investigated in [19]. Due to its small beam spot, the authors used an X-ray beam for selective irradiation on specific locations within a chip. The dose rate was 169-274 rad(SiO_2)s^{-1} during the experiment, with dose rate variability of no more than 6 %. The simplified architecture of the device studied in this work is depicted in fig. 4. The authors used a 1 MB parallel FRAM prototype fabricated in a 130-nm CMOS process, with PZT thin film as a ferroelectric capacitor to investigate the radiation resistance of the following function blocks: memory array, sense amplifier, row decoder, column decoder, and I/O port. Irradiation tests were performed at room temperature with five samples. Whole-chip irradiation was performed on two test devices, with Co-60 as a gamma ray source and a dose rate at 80 rad(SiO_2)s^{-1}. Following irradiation, observed memory blocks exhibit different error signatures and performance degradation at different levels of radiation. Results showed that the most radiation sensitive part of the FRAM cell was the sense amplifier due to its working mode which is sensitive to shifts in the NMOS parmeter. Due to the circuit structure of the ferroelectric capacitor and high radiation resistance, a higher tolerance to radiation of the memory array compared to that of the peripheral circuit was noted. The address decoder and I/O ports proved not to be major factors contributing to the TID-induced functional failure of the FRAM device. The results on whole chip irradiation indicated that Co-60 gamma radiation causes more serious degradation due to higher charge yield, stronger penetration and wide field damage, whereas the dose enhancement effect is considered not to play a dominant role.

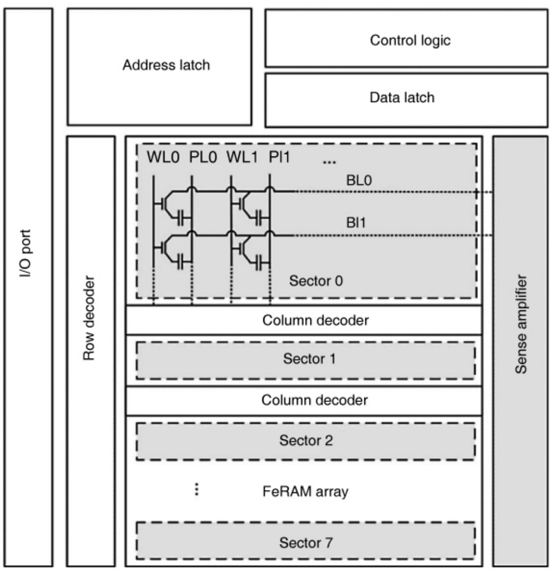

Figure 4. FRAM architecture

Summary

Numerous researches have proved that ferroelectric films are very radiation resistant. However, FRAM devices are not robust enough for severe radiation environments due to poor TID hardness of the peripheral CMOS circuits. More effort should be made to locate weak spots in terms of radiation resistance and hardening peripheral CMOS circuits in order to improve their performance and enhance overall FRAM reliability.

MAGNETORESISTIVE RANDOM ACCESS MEMORY

Magnetoresistive random access memory (MRAM) is a new and promising non-volatile, low power memory technology whose key attributes are unlimited endurance and high speed read and write operations. MRAM uses the magnetic tunnel junction (MTJ) for data storage. The central component of MRAM is a MTJ which is formed from two ferromagnetic layers separated by a thin tunnel insulator barrier [20]. The structure of the MRAM cell is shown in fig. 5. The magnetic Pinned Layer (or reference layer) is set to a fixed magnetic polarity, while the Magnetic Free Layer (or storage layer) has freely imposable magnetization. If the layers have the same polarity (relative magnetic orientation is parallel) the resistance of the MTJ structure is low and this represents logic „1"; if the polarity of the layers is opposite (relative magnetic orientation is anti-parallel) the resistance is high and this represents logic „0". The magnetic field in the storage layer changes orientation when a bit line polarizing switches the current passing through the MTJ structure. The MTJ switches to high resistance state when the current direction is from reference to storage layer; if the direction of the current is opposite, MTJ switches to low resistance state.

The Toggle MRAM approach evolved from the search for a means to increase the operating window of the MRAM write operation so that a significant margin exists between the level of fields required for switching all bits and the level at which disturbances occur [21]. The structure of the Toggle MRAM cell is similar to that of the conventional MTJ except for the free layer which consists of two weakly anti-parallel coupled ferromagnetic layers. In addition to the

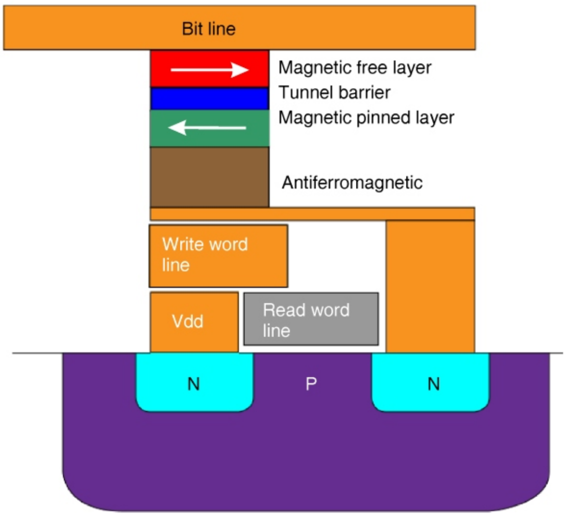

Figure 5. MRAM cell structure

changes in the free magnetic layer, the long axis of the structure lies at approximately 45 degrees with respect to the WL, as opposed to being parallel to the WL. The read operation is essentially unchanged, with the magnetic orientation of the lower free layer determining the effective resistance of the structure [22].

Spin-transfer torque (STT) RAM is a MRAM memory with better scalability compared to the conventional MRAM. STT is an effect in which the orientation of a magnetic layer in a magnetic tunnel junction or spin valve can be modified using a spin-polarized current. STT technology has the potential of creating MRAM devices combining low current requirements and reduced cost; however, the amount of current needed to reorient the magnetization is at present too high for most commercial applications [23]. The major difference between STT-MRAM and MRAM is the way information is recorded. In MRAM, the switching between two memory states is achieved by the application of an external field, which is generated by passing the current through two metallic lines: word and bit lines, as shown in fig. 6 [24].

One of the most important limitations of conventional MRAM is scalability and power consumption. The power required for MTJ switching increases with a decrease in the size of the MRAM cell since the field required for switching increases, which means more current has to pass through the MTJ. „Half select" is another important issue in MRAM. The MTJ switches when a current passes through two orthogonal metallic lines: the bit line and the word line. Other cells located below or above the metallic lines also experience a magnetic field. Although smaller in magnitude, this field can also result in the switching of these cells. The problem can be alleviated by using anti-ferromagnetic (SAF) free layers. In STT-MRAM, the „half problem" is eliminated due to the fact that the switching current passes directly and entirely through magnetic layers in the selected MTJ cell. Controlling resistance uniformity, switching the behavior of magnetic bits and integration of MTJ with CMOS are some of the key challenges for a successful implementation of this technology [25].

Radiation hardness of MTJ with MgO was analyzed in [26]. MTJ samples were exposed to gamma and neutron radiation field. MTJ devices in the experimental group were exposed to a gamma radiation field containing a Co-60 source, the dose rate being constant at 9.78 radmin^{-1}. The initial dose was 5.9 Mrad (Si) after which they were again characterized. Irradiation was then continued for a cumulative dose of 10 Mrad. Due to the much higher carrier concentration in metal-based MTJ, the ionized carriers have an insignificant effect on the transport properties. It was shown that MgO-based MTJs are highly tolerant of gamma radiation, particularly in comparison to silicon field-effect transistors which have been shown to degrade with gamma ray exposure even as low as 100 krad [27]. The characteristics of neutron radiation were as follows: total epithermal neutron fluence up to 2.9 10^{15} cm^{-2}, with the flux at 5 10^{10} cm^{-2} at 50 kW and neutron energies ranging from 0.1 eV to 10 MeV. It was shown the MTJs are insensitive to the epithermal neutron fluence of 2.9 10^{15} cm^{-2}, a dose which could cause irreversible displacement damage in the silicon dioxide and high-*k* semiconductor materials. This is due to the fact that soft magnetic metals and alloys have a structure that is insensitive to epithermal neutron radiation.

In [28], TID and heavy ion testing were performed on a 1 Mbit MRAM. TID effects were evaluated using Aracor X-ray as well as Co^{60} testing. It was concluded that changes in silicon and magnetic devices show no significant shifts, indicating that charge trapping and

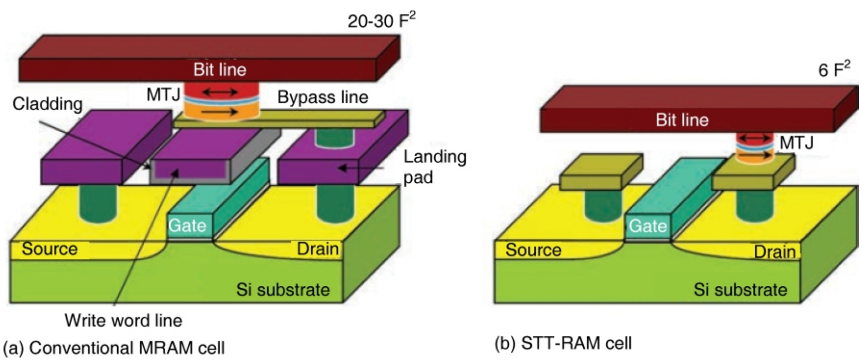

Figure 6. (a) Conventional MRAM cell and (b) STT MRAM cell

threshold shifts in the silicon, insulating tunneling barrier and band structure, as well as carrier population changes in metals, are insignificant. Read, write, and timing performance parameters showed no significant changes from pre-irradiation values through 1 Mrad TID. At a ion fluence in excess of 9 10^9 cm^{-2} using 940 MeV Bi ions at LET of 100 $MeVcm^2mg^{-1}$, a negligible change in bit resistance was observed. For LET values below approximately 70 MeV cm^2mg^{-1}, hard failures were not observed. As LET values increased above approximately 78 MeV cm^2mg^{-1} and as ion fluencies increased above10^8 cm^{-2}, hard failures in populations of MTJ bits were induced. A significant reduction in bit resistance was observed, corresponding to the shortening of resistance across the insulating tunneling barrier.

Total ionization effects on commercial Freescale MR2A16A MRAM were studied in [29, 30]. The tests were carried out at 25°C using the JPL cobalt-60 facility at a dose rate of 25 $rad(Si)s^{-1}$. The Freescale MRAM were programmed with random numbers and tested dynamically *in situ* with the following three modes: (1) read-only loops, (2) read-program-read loops, (3) a combination of mode 1 and 2 above. Five MRAM, serial numbers FS001-FS005 were tested during irradiation, with different modes; FS001 was tested with mode 2, FS002 with mode 3, while the rest were tested with mode 1. All five tested devices had no errors at 40 krad(Si) and below. Device FS001 started having 2 read errors at 45 krad(Si), and had more than 130 read errors at the accumulated dose of 55 krad(Si). Two devices, FS003 and FS004, had no failure at 60 krad(Si) and below with mode 1. Device FS002 showed only 11 read errors at 50 krad(Si). These results showed that most MRAM devices would survive the total accumulated dose of up to 60 krad(Si). The main area sensitive to radiation in MRAMs was the CMOS circuitry. All five devices were electrically tested after they were allowed to anneal at 25 °C for 24 hours. Three devices, FS002-003 and FS005 could be reprogrammed with new data after 120 hours at 25 °C, whereas the other two recovered after 30 days.

Analysis of the effects of neutron and alpha particle radiation on commercial 4Mbit toggle MRAM memory was given in [31]. The tests were conducted in both static and dynamic mode. A quasi mono energetic neutron beam was used, with particles of energies of 25 MeV, 50 MeV, and 80 MeV in a beam with a diameter of 36 cm. No SEU or latch-up events were observed in static or dynamic mode. In normal operating conditions, a neutron radiation cannot change the MTJ physical structure nor can it change the stored information since it does not induce any significant magnetic field. Thus, a bit cell upset occurring while the memory is in static mode would be quite impossible. The authors concluded that the soft error resilience of this memory was sufficient to keep the memory error free at least for energies up to 80 MeV. Alpha particle irradiation has been performed using a Californium source (Cf-252). Several hours of non-stop experiments for each chip were conducted with Toggle MRAM operating under static and dynamic modes, with different types of tests (static, dynamic stress, March C–, MATS+). Results showed that the 4 Mbit Toggle MRAM did not suffer from any types of upsets during alpha particle radiation. The only effect brought by heavy ion radiation is the small decrease in minimum resistance (parallel state) and a small increase in maximum resistance (antiparallel state).

Radiation assessment of Freescale Semiconductor 4 Mbit MR2A16A MRAM memory was analyzed in [32]. The authors used the K500 cyclotron at Texas A&M University (TAMU) as a source of heavy ion radiation. This facility was able to provide ions with a relatively high energy (40 MeV/nucleon). Test results showed that MR2A16A was very sensitive to SEL and should be used with caution. The LET latchup threshold for room temperature was around 10 MeV cm^2mg^{-1}. At 85 °C, the device had a latch-up threshold between a LET of 7 MeV cm^2mg^{-1} and 10 MeV cm^2mg^{-1}. The conclusion is that this device is suitable for certain specific applications and, in order to minimize the likelihood of occurrences of SEL and consequently the risk of SEL, the device should be powered on for a short period of time during the mission.

Radiation studies of STT materials and devices were given in [33]. Radiation effects were studied solely on magneto-resistive devices, separate from supporting CMOS circuitry. Spin-transfer torque film stacks and devices were exposed to a cobalt-60 gamma radiation source (total dose up to 10 Mrad(Si)), as well as to 2 MeV and 220 MeV protons. Schematic representation of the STT film stack is given in fig. 7. Experiments on gamma radiation effects in STT torque film stacks were designed by utilizing vibrating sample magnetometry (VSM), ferromagnetic resonance (FMR) and current-in-plane-tunneling (CIPT). Post-radiation measurements performed using VSM showed no measureable differences in magnetization and coercivities of the MTJ layer stack to a dose of 10 Mrad(Si). Ferromagnetic resonance measurements showed no measurable changes to the effective magnetization and to the free-layer damping parameter α. The current-in-plane-tunneling method was used to perform measurements to characterize the susceptibility of the RA product and TMR to Co-60 irradiation. The measurements were performed on one stack before and after Co-60 irradiation to 1 Mrad(Si) and on the second stack before and after irradiation to 10 Mrad(Si). Results showed no significant changes on state retention. Spin-transfer torque devices were irradiated using the same sources, to a total dose of 1 Mrad(Si). The switching characteristics of these devices didn't change after irradiation and showed no changes in bit-state or write performance.

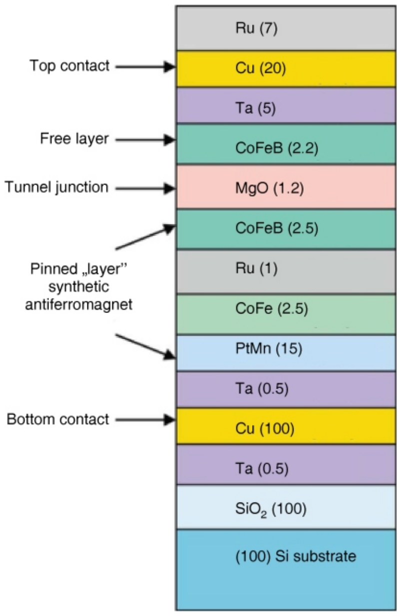

Figure 7. Spin-transfer torque film stack with the thickness of each layer listed in nanometers

Summary

MRAM devices proved to be radiation resilient in the field of neutron and gamma radiation for doses up to 10 Mrad. Ions with a relatively high energy (40 MeV/nucleon) may have an impact on commercial MRAM causing SEL, whereas heavy ion radiation induces hard errors for high LET values (above 78 MeV cm^2mg^{-1}) and high ion fluencies (above 10^8 cm^{-2}). Experiments on gamma radiation showed good radiation immunity of STT MRAM which appears to be a promising technology for use in radiation-hardened environments. However, radiation issues may arise in the CMOS part of MRAM as it is most sensitive to irradiation.

PHASE CHANGE MEMORY

Phase change memory (PCM) is considered to be one the most promising candidates to replace floating gate flash memories due to its good stability, high density and speed, simple cell structure, fast writing and reading ability, good endurance, non-volatility, and good compatibility [34]. PCM employs chalcogenide materials, such as the $Ge_2Sb_2Te_5$ alloy (GST), to store information. These materials can reversibly change phase from amorphous to polycrystalline and *vice versa*. In polycrystalline state, which can be denoted as the SET state, the material has low resistance, whereas in the amorphous state (RESET state), the material is characterized by a high resistance value. Typically, a cell in the amorphous state is regarded as logic '0' and a cell in the crystalline state is regarded as logic '1'. The transition between states is achieved by properly heating and cooling the material. Figure 8 shows the sandwich-like structure of a typical PCM cell. The phase change material is placed between two TiW electrodes. These two TiW layers are isolated by ZnS-SiO_2 films.

Phase change material is initially in crystalline state because the processing temperature of the metal interconnecting layers is sufficient to crystallize the phase change material. Switching the PCM cell to the amorphous phase (writing a logic '0') is performed by heating the active region up to the melting temperature and then rapidly cooling it by applying a large electrical current pulse for a short time period. To write a logic '1' into the cell, it needs to be switched back to crystalline state. It is done by applying a low amplitude current pulse to anneal the programming region of the cell at a temperature above its crystallization temperature, but below its melting temperature over a period of time. Reading the content of the cell is done by passing an electrical current small enough not to induce any heating effect nor disturb a cell's state. The reading operation implies distinguishing between the low resistance and high resistance state.

Heavy ion irradiation effects (both TID and SEE) on phase change memories (PCM) with MOSFET and BJT selectors and the effect of irradiation on the retention characteristics of these devices were studied in [35]. Post-irradiation effects were mostly due to the degradation of the selector transistor. It was noted that BJT transistors are more immune than MOSFET to TID since the irradiations took place at a high dose rate (10 krad $(SiO_2)s^{-1}$). Namely, high dose rate represents the worst case condition for TID testing of chips with MOSFET selectors, where most of the changes result from charge trapping in the MOSFET gate oxides and into the STI, whereas a low dose-rate irradiation could produce larger changes in BJT gain. Heavy ions do not produce any variation of the current measured in the cells, confirming the resilience of the GST phase change material to the ionization damage produced by high energy LET particles. Retention ex-

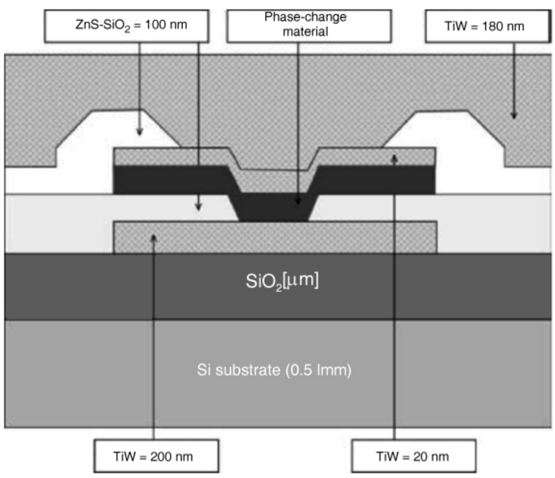

Figure 8. PCM cell structure

periments demonstrate that PCM retention capabilities are not compromised by ionizing irradiation and that the radiation induced changes reduce with time.

Investigation of X-ray irradiation effects on PCM cell array was conducted in [36]. A 50-nm thick chalcogenide $Ge_2Sb_2Te_5$ film deposited by rf magnetron sputtering was used as storage medium for the PCM cell. The resistance of HR state was two orders of magnitude larger than that of the LR state from the resistance measurement, and the threshold current needed for phase transition of our fabricated PCM cell array was very low (several A). An X-ray total dose radiation test was carried out on the PCM cell array showing good total dose radiation tolerance for a total dose of up to 2 10^6 rad(Si), which makes it attractive for space-based applications.

Gerardin *et al*. [37] analyzed the sensitivity of 45-nm phase change memory cells to neutrons and heavy ions. No errors were observed after neutron irradiation with a terrestrial-like spectrum. With heavy ions, a radiation-induced bit occurred in PCM cells set to crystalline state when heavy ions with a high linear energy transfer (only rarely found in space environment) strike a cell at an angle along the word line. The effect is likely due to amorphization of the GST material close to the heater-chalcogenide interface. It was found that the threshold angle and the threshold LET required to produce upsets were about 60 °C and larger than 38 MeV cm^2mg^{-1}, respectively. No effect at all was observed in cells set to the amorphous state prior to irradiation. Physical mechanisms have been investigated, leading to the conclusion that the thermal spike model may explain the observed results.

The TID electron irradiation effects on commercial 4 Mbit PCM arrays were studied in [38]. Four test chips were irradiated with 8-MeV electrons at increasing doses of 1, 3, 10, and 30 Mrad(SiO_2) with a dose rate of 13 krad(SiO_2)s^{-1}. The authors observed small variations of SET and RESET distributions even at high doses, primarily caused by the degradation of the bit line and word line selection MOSFET. Small variations could be due to the degradation of GST, but this should have only secondary effects on chip functionality with respect to the changes in electrical properties induced by radiation on MOSFET. Radiation did not compromise SET and RESET operation functionality, proving high robustness of PCM against ionizing radiation.

Monte Carlo simulations of proton irradiation on phase change memory cells were conducted and the proton dose, in both the whole memory cell and in its active layer, was calculated in [39]. This type of approach in investigating radiation effects is valuable since it allows the assessment of the proton dose and the overview of radiation effects in layers of interests for realistic proton fluences, whereas actual experiments can hardly separate the influence of radiation on the PCM cell alone without including the effects on peripheral circuits [40]. The memory cell was modeled by a multi-layer stack consisting of two TiW electrodes and ZnS-SiO_2 films as insulators. Three most commonly used materials ($Ge_2Sb_2Te_5$, $AgSbSe_2$, and $Si_2Sb_2Te_5$) were used for the active region. The effects of proton beam irradiation were investigated for different thicknesses of PCM material and different proton energies. Values of proton energy loss were used to calculate the absorbed dose in the phase change layer and the entire cell, and the obtained values for the absorbed dose were around 104 Gy. The results of these simulation-based calculations showed that the investigated materials were most sensitive within the narrow range of proton energies between 75 and 100 keV. An increase in material thickness caused a significant increase in the active layer dose in the critical proton energy range, whereas the absorbed dose in the whole PCM cell remained nearly constant. Proton beam irradiation can induce thermal heating of the active material and accumulation of atom displacement which can affect the stability of the PCM cell.

Summary

Investigation of radiation effects on PCM remains an interesting topic for research. Current results indicate a high resistance of PCM against ionizing radiation, also providing evidence of CMOS circuitry as the most sensitive part of these devices. However, the authors used only rad-hard CMOS technology, while no investigation of radiation effects on PCM integrated with non rad-hard technology was carried out. The effect of the interaction between high energy particles and GST through non-ionizing processes could produce structural modifications of the GST alloy and this needs to be further investigated.

CONCLUSION

Resistive memory technologies appear to be a promising memory technology of the future due to their speed, endurance, low leakage power, high density and good compatibility with CMOS. The investigations of radiation effects on resistive memory technologies confirmed the high tolerance and immunity of these devices to ionizing radiation, positioning them as good candidates for the leading memory technology for applications in harsh environments such as aerospace and nuclear engineering. However, our experiments have proved poor radiation hardness of the peripheral CMOS circuits since they are most sensitive to irradiation, thus possibilities to conduct more radiation hardening research in this area should be considered.

ACKNOWLEDGEMENTS

The Ministry of Education, Science and Technological Development of the Republic of Serbia supported this work under contract 171007.

AUTHORS' CONTRIBUTIONS

All signed authors participated in the drafting of this article.

REFERENCES

[1] Lee, B. C., *et al*., Phase-Change Technology and the Future of Main Memory, *IEEE Micro, 30* (2010), 1, pp. 131-141

[2] Vujisić, M., *et al*., Comparison of Gamma Ray Effects on Eproms and e^2proms, *Nucl Technol Radiat, 24* (2009), 1, pp. 61-67

[3] Dolićanin, E., Gamma Ray Effects on Flash Memory Cell Arrays, *Nucl Technol Radiat, 27* (2012), 3, pp. 284-289

[4] Yu, S., Resistive Random Access Memory (RRAM) : From Devices to Array Architectures, Morgan & Claypool, 2016

[5] Wong, H.-S. P. *et al*., Metal-Oxide RRAM, *Proceedings of the IEEE, 100* (2012), 6, pp. 1951-1970

[6] Yuan, F., *et al*., γ-Ray Irradiation Effects on TiN/HfO_x/Pt Resistive Random Access Memory Devices, *Proceedings*, IEEE Aerospace Conference, June, 2015

[7] He, X., Geer, R. E., Heavy Ion Radiation Effects on TiN/HfO_2/W Resistive Random Access Memory, *Proceedings*, IEEE Aerospace Conference, Big Sky, Mont., USA, March, 2013

[8] Wang Y., *et al*., Highly Stable Radiation-Hardened Resistive-Switching Memory, *IEEE Eelectron Device Letters, 31* (2010), 12, pp. 1470-1472

[9] Holt, J., *et al*., Radiation Testing of Tantalum Oxide-based Resistive Memory, *Proceedings*, IEEE International Integrated Reliability Workshop (IIRW), South Lake Tahoe, Cal., USA, 2015, Oct., pp. 155-158

[10] Zhang, L., *et al*., Total Ionizing Dose (TID) Effects on TaOx-Based Resistance Change Memory, *IEEE Transactions on Electron Devices, 58* (2011), 8, pp. 2800-2804

[11] He, X., *et al*., Superior TID Hardness in TiN/HfO_2/TiN RRAM after Proton Radiation, *IEEE Transactions on Nuclear Science, 59* (2012), 5, pp. 2550-2555

[12] ***, The Impact of X-Ray and Proton Irradiation on HfO_2/Hf-Based Bipolar Resistive Memories, *IEEE Transactions on Nuclear Science, 60* (2013), 6, pp. 4540-4546

[13] Yuan, F., *et al*., Total Ionizing Dose (TID) Effects of γ-Ray Radiation on Switching Behaviors of Ag/AlO_x/Pt RRAM Device, *Nanoscale Research Letters, 9* (2014), 1, pp. 1-6

[14] Fox, G. R., *et al*., Current and Future Ferroelectric Nonvolatile Memory Technology, *Journal of Vacuum Science & Technologym B 19* (2001), 1967

[15] Shen, J., *et al*., Assessment of TID Effect of FRAM Memory Cell under Electron, X-ray and Co-60 γ-Ray Radiation Sources, *IEEE Transactions on Nuclear Science, 64* (2017), 3, pp. 969-975

[16] Gupta, V., *et al*., Heavy-Ion Radiation Impact on a 4 Mb FRAM under Different Test Conditions, *Proceedings,* 15^{th} European Conference on Radiation and its Effects on Components and Systems (RADECS), Sept., 2015

[17] Zanata, M., *et al*., Ionizing Radiation Effect on Ferroelectric Nonvolatile Memories and Its Dependence on the Irradiation Temperature, *IEEE Transactions on Nuclear Science, 55* (2008), 6, pp. 3237-3245

[18] Nguyen, D. N., Scheick, L. Z., TID Testing of Ferroelectric Nonvolatile RAM, *Proceedings*, IEEE Radiation Effects Data Workshop, Cornell Univ., New York, 2001, pp. 57-61

[19] Gu, K., *et al*., Total Ionizing Dose Sensitivity of Function Blocks in FRAM, *Microelectronics Reliability, 55* (2015), March, pp. 873-878

[20] Tehrani, S., *et al*., Magnetoresistive Random Access Memory Using Magnetic Tunnel Junctions, *Proceedings of the IEEE, 91* (2003), 5, pp. 703-714

[21] ***, A 4-Mb 0.18-/spl mu/m 1T1MTJ toggle MRAM with Balanced Three Input Sensing Scheme and Locally Mirrored Unidirectional Write Drivers, *IEEE Journal of Solid-State Circuits, 40* (2005), 1, pp. 301-309

[22] Maffitt, T. M., Design Considerations for MRAM, I*BM Journal of Research and Development, 50* (2006), 1, pp. 25-39

[23] Meena, J. S., *et al*., Overview of Emerging Nonvolatile Memory Technologies, Nanoscale Research Letters 20149:526, Sept., 2014

[24] Apalkov, D., *et al*., Spin-Transfer Torque Magnetic Random Access Memory (STT-MRAM), *ACM Journal on Emerging Technologies in Computing Systems (JETC) – Special Issue on Memory Technologies, 9* (2013), 2, Article No. 13

[25] Slaughter, J. M., *et al*., Fundamentals of MRAM Technology, *Journal of Superconductivity, 15* (2002), 1, pp. 19-25

[26] Ren, F., *et al*., Radiation Tolerance of Magnetic Tunnel Junctions with MgO Tunnel Barriers, *IEEE Transactions on Nuclear Science, 59* (2012), 6, pp. 3034-3038

[27] Pejović, M. M., *et al*., Successive Gamma-Ray Irradiation and Corresponding Post-Irradiation Annealing of pMOS Dosimeters, *Nucl Technol Radiat, 27* (2012), 4, pp. 341-345

[28] Katti, R. R., *et al*., Heavy-Ion and Total Ionizing Dose (TID) Performance of a 1 Mbit Magnetoresistive Random Access Memory (MRAM), *Proceedings*, IEEE Radiation Effects Data Workshop, Quebec City, QC, Canada, July, 2009

[29] Nguyen, D.,N., Irom, F., Total Ionizing Dose (TID) Tests on Non-Volatile Memories: Flash and MRAM, *Proceedings*, IEEE Radiation Effects Data Workshop, July, 2007

[30] Nguyen, D. N., Irom, F., Radiation Effects on MRAM, *Proceedings*, 9^{th} European Conference on Radiation and Its Effects on Components and Systems RADECS 2007, Sept., 2007

[31] Tsiligiannis, G., *et al*., Testing a Commercial MRAM under Neutron and Alpha Radiation in Dynamic Mode, *IEEE Transactions on Nuclear Science, 60* (2013), 4, pp. 2617-2622

[32] Elghefari, M., McClure, S., Radiation Effects Assessment of MRAM Devices, Pasadena, Cal., USA, Jet Propulsion Laboratory, National Aeronautics and Space Administration, 2008, URI: http://hdl.handle.net/2014/40809

[33] Hughes, H., *et al*., Radiation Studies of Spin-Transfer Torque Materials and Devices, *IEEE Transactions on Nuclear Science, 59* (2012), 6, pp. 3027-3033

[34] Kinam, K., Lee, S. Y., Memory Technology in the Future, *Microelectronic Engineering, 84* (2007), 9-10, pp. 1976-1981
[35] Gasperin, A., *et al*., Analysis of Proton and Heavy-Ion Irradiation Effects on Phase Change Memories with MOSFET and BJT Selectors, *IEEE Transactions on Nuclear Science, 55* (2008), 6, pp. 3189-3196
[36] Wu, L., *et al*., Total Dose Radiation Tolerance of Phase Change Memory Cell with GeSbTe Alloy, *Chinese Physics Letters, 23* (2006)
[37] Gerardin, S., *et al.*, Heavy-Ion Induced Single Event Upsets in Phase-Change Memories, *Proceedings*, IEEE International Reliability Physics Symposium, Waikoloa, HJ, USA, June, 2014
[38] Gasperin, A., *et al*., Total Ionizing Dose Effects on 4 Mbit Phase Change Memory Arrays, *IEEE Transactions on Nuclear Science, 55* (2008), 4, pp. 2090-2097
[39] Zdjelarevic N.S., et al., Simulation-Based Calculations of the Proton Dose in Phase Change Memory Cells, *Nucl Technol Radiat, 28* (2013), 3, pp. 299-307
[40] Marjanović. N. S.. *et al*., Simulated Exposure of Titanium Dioxide Memristors to Ion Beams, *Nucl Technol Radiat, 25* (2010), 2, pp. 120-125

Received on June 15, 2017
Accepted on Novembver 11, 2017

Ирфан С. ФЕТАХОВИЋ, Един Ђ. ДОЛИЋАНИН,
Ђорђе Р. ЛАЗАРЕВИЋ, Борис Б. ЛОНЧАР

ПРЕГЛЕД РАДИЈАЦИОНИХ ЕФЕКАТА У НОВИМ ПОСТОЈАНИМ МЕМОРИЈСКИМ ТЕХНОЛОГИЈАМА

У овом раду дат је преглед радијационих ефеката у новим, постојаним меморијским технологијама. Приказана су истраживања радијационе отпорности резистивних меморија са случајним приступом, фероелектричних меморија са случајним приступом, магнетнорезистивних меморија са случајним приступом и меморија са променом фазе, у случајевима када су ове меморије подвргнуте различитим врстама зрачења. Резултати доказују високу радијациону толеранцију испитиваних уређаја што их чини добрим кандидатима за примену у радијационо-интензивним окружењима.

Кључне речи: постојана меморија, радијациони ефекат, резистивна РАМ, фероелектрична РАМ, магнетнорезистивна РАМ, меморија са променом фазе