# RELIABILITY OF COMPUTER MEMORIES IN RADIATION ENVIRONMENT

by

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**The aim of this paper is examining a radiation hardness of the magnetic (Toshiba MK4007 GAL) and semiconductor (AT 27C010 EPROM and AT 28C010 EEPROM) computer memories in the field of radiation. Magnetic memories have been examined in the field of neutron radiation, and semiconductor memories in the field of gamma radiation. The obtained results have shown a high radiation hardness of magnetic memories. On the other side, it has been shown that semiconductor memories are significantly more sensitive and a radiation can lead to an important damage of their functionality.**

*Key words: magnetic memory, semiconductor memory, radioactive reliability, gamma radiation, neutron radiation*

## INTRODUCTION

Computer memories, as to the way data are stored can be divided into: magnetic, semiconductor, and optical ones. Based on the medium storing the data, memories can be divided into mechanical, movable; optical solid state and ferroelectric. Hard disk and bubble storage belong to mechanical memories; compact disk and holographic recording belong to optical memories. Bipolar, MOS and CCD represent semiconductor memories [1].

Computer magnetic memories possess a domain structure and they are very resistant to the outer influences. Their good side is a high accuracy level and stability. Programmable semiconductor memories are made today in CMOS technology and can be divided into two primary groups: random access memory (RAM) that can be static (SRAM) and dynamic (DRAM), and ROM, where erasable programmable read only memory (EPROM) and electrically erasable programmable read only memory (EEPROM) belong to. Random access memory memories are unreliable since they lose their content when the power supply is switched off. Random access memory memories are more reliable and they have a constant content that is not lost when the power supply is switched off. EPROM memories have the ability of deleting their content and they can be reprogrammed by a user. Unfortunately, their content can be deleted only by using expensive ultraviolet equipment. On the other side, EEPROM components have a possibility of deleting content electrically with out using expensive ultraviolet equipment [1].

Electronic memory components are widely used in military and medical applications, nuclear power plants, high altitude avionics and space applications. This represents significant risk since the exposure of integrated circuit electronics to ionizing radiation can lead to transient or permanent damage of their functionality. Therefore, it is very important to test radiation hardness of computer memory devices and to assess their radiation reliability.

Three types of errors can occur when electronic components are exposed to ionizing radiation: soft errors, hard errors and failures. Soft errors occur when a radiation event causes a reverse of data bit in a memory cell. These errors are not permanent and can be reversed by entering new data or reprogramming a memory. On the other hand, hard errors are irreversible and destructive.

It has been shown that a (relatively) high total dose, exceeding 1000 Gy ($SiO_2$), is needed to induce errors in the flash memory array, but threshold voltage shifts are all but negligible even at lower doses [2]. Testing on commercially available 2 Gb NAND flash non-volatile memory, both for total ionizing dose

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(TID) radiation damage and for single event effects (SEE) from heavy ion exposure have shown that static errors rise abruptly above 750 Gy ($SiO_2$) while dynamic errors rise quickly at even lower doses [3].

The aim of this paper is to examine radiation hardness of magnetic and semiconductor computer memories. Magnetic memories have been exposed to ($n$, $\gamma$) radiation field, and semiconductor memories (EPROM and EEPROM) have been tested in the field of gamma radiation.

## EXPERIMENTAL PROCEDURE

The examinations of magnetic memories radiation hardness have been performed in the field of ($n$, $\gamma$) radiation, where a dominant is the neutron radiation. Indeed, it is known from the theory that neutron effects are the most dangerous for domain structure degradation [4].

Irradiation of hard disks (Toshiba MK4007 GAL), with the storage capacity of 40 GB, was performed a few years ago in the field of reactor RB of the Public Company Nuclear Facilities of Serbia, Belgrade, Serbia. In the magnetic memory layer, the information was written in a binary form, *i. e.*, states “0” or “1”, matching the appropriate states of a remanent induction of an opposite orientation. The transition from one binary state into the other was performed with an outer action. The examinations were performed by a standard procedure for computer components. One hard disk was set into the center of a reactor system, and two hard disks were set the periphery, out of which one was covered with a Cd layer that absorbs low-energetic neutrons. A binary content of all zeros was written into the hard disks, all ones and a leading one (1010), respectively, in all locations.Then, the content was read after irradiation, with the aim to confirm a number of locations where the content had been changed, *i. e.*, the ones that had reversible or irreversible damages. Irradiations were performed for the reactor power $P = 10$ W, with a time interval $\tau = 0.5$ h in the first phase of the experiment, and at the same power and with the same time interval in the second phase of the experiment.

The calculation of space-energy distribution of a neutron flux density and maximum equivalent neutron doses at the given point of the HERBE system ($r$, $z$) was performed with the VEGA program [5].

The examination of a radiation hardness of EPROM and EEPROM has been performed in Metrology-Dosimetry Laboratory of the Vinča Institute of Nuclear Sciences, Belgrade, Serbia. In the field of gamma radiation $^{60}Co$, the samples of AT 27C010 EPROM have been examined, with their memory capacity of 1 MB, and AT 28C010 EEPROM, with their memory capacity of 1 MB. Prior to the beginning of irradiation, the same memory content was written into all memory samples, *i. e.*, a logical state “1”. It is much more sensitive to radiation than a logical state “0”., for their higher threshold voltage changes for the same values of the absorbed dose [6, 7]. At the same time, constant voltage impulses were used. The radiation field dimensions were 8 cm  8 cm.The absorbed dose of gamma radiation was changed with the change of irradiation time and distance between sources and the examined memory components. Twenty samples of the stated components have been examined, and the obtained average results are presented in the paper. From the first observed faults, *i. e.*, changes from the logical state of the memory cell from “1” to “0”, the dose has been gradually increased in steps per 10 Gy for EPROM and 50 Gy for EEPROM components [8-10].

## RESULTS AND DISCUSSION

### Magnetic memories (hard disk)

During a neutron activation uranium fission takes place, and then numerous uranium descendants appear that are dominantly gamma radioactive. Due to a large number of photons that appeared, it was difficult to calculate the flux and gamma radiation dose; and they were measured with a calibration instrument set in the given points of the HERBE system. In this way, the calibration curves obtained showed the absorbed gamma dose rate in the center of VKH HERBE system, which depends on the reactor power and the absorbed gamma dose rate in the lateral side of RB reactor with HERBE system [11].

From those curves, actually based on the obtained fitted dependences, the gamma dose rate was determined.

Employing the VEGA program, there was found a dependency of the neutron flux and the hard disk, at the height of $h = z = 70$ cm, depending on $r$ for all four energetic groups, shown in fig. 1. In the case $r = 20$ cm,

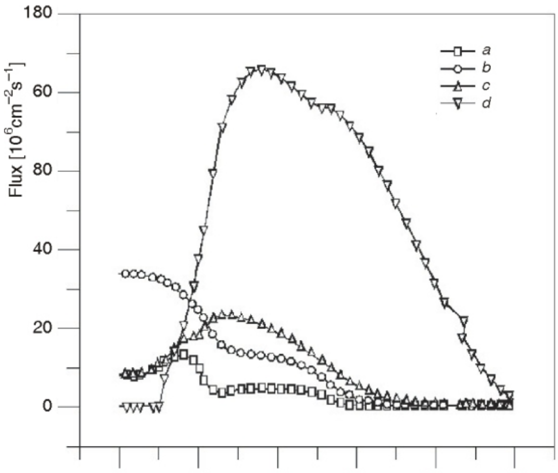


**Figure 1. Neutron flux density as a function of $r$ at the height of $h = z = 70$ cm for all four energetic groups**

the dependency of the neutron flux on $h = z$ is shown in fig. 2. The dependency of neutron flux on the energy for the point A ($r$ = 20 cm, $h = z$ = 70 cm), *i. e.*, in the center of HERBE system, is shown in fig. 3. Based on the above-mentioned, the calculation of the total absorbed dose rate was made, as a sum of the absorbed dose rates for all four energetic groups, at the given point. It amounted to 4.58 Gy/h. Likewise, by applying VEGA program, a dependency was determined of the neutron flux and the hard disk set at the periphery of the reactor's vessel, shown in figs. 4 and 5. In addition, a dependency was observed of the neutron flux and energy for the point B ($r$ = 100 cm, $h = z$ = 70 cm), shown in fig. 6. The calculated total absorbed dose rate was 0.038 Gy/h. In the case of hard disks that were at the same place as the previous ones, but covered with the layer Cd, they had absorbed low-energetic neutrons of the fourth group, thus the total absorbed dose rate was 0.00056 Gy/h, influenced only by the neutrons of the first three energetic groups.

The gamma dose rate was determined based on the obtained dependency [12]

$$\dot{D}_{\gamma} \quad 24.1301 \; 10^{\;3} P^{0.980012} \qquad (1)$$

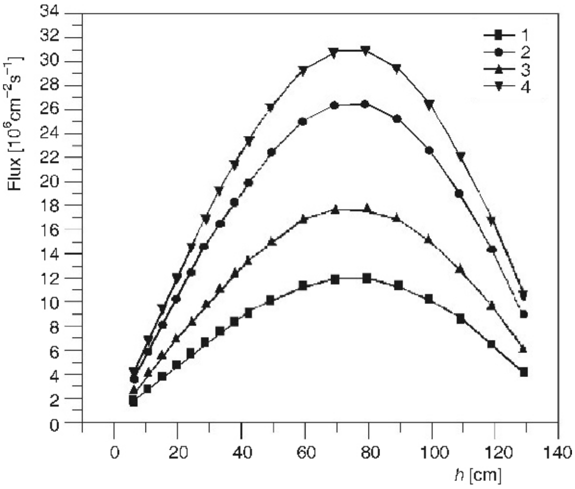


**Figure 2. Neutron flux density as a function of *h* at *r* = 20 cm for all four energetic groups**

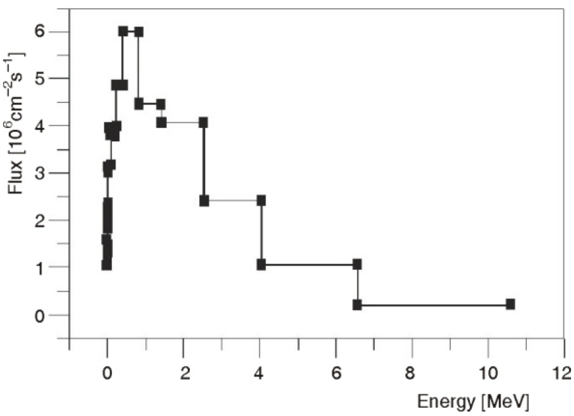


**Figure 3. Neutron flux density as a function of energy in the point A (*r* = 20 cm, *h* = 70 cm), HERBE system**

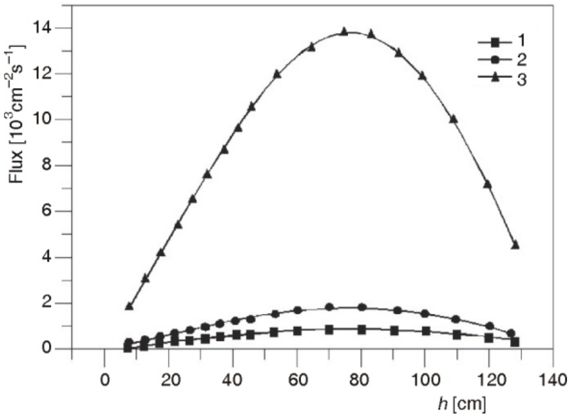


**Figure 4. Neutron flux density as a function of *h* at *r* = 100 cm for first three energetic groups (hard disks covered with Cd)**

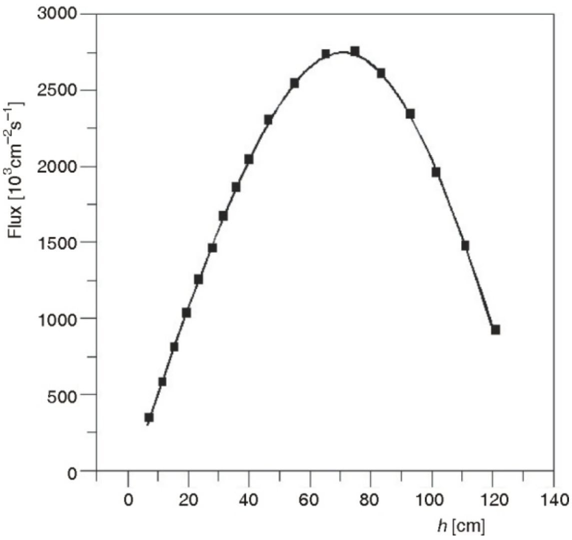


**Figure 5. Neutron flux density as a function of *h* at *r* = 100 cm for the fourth energetic group (hard disks at the system periphery, not covered with Cd)**

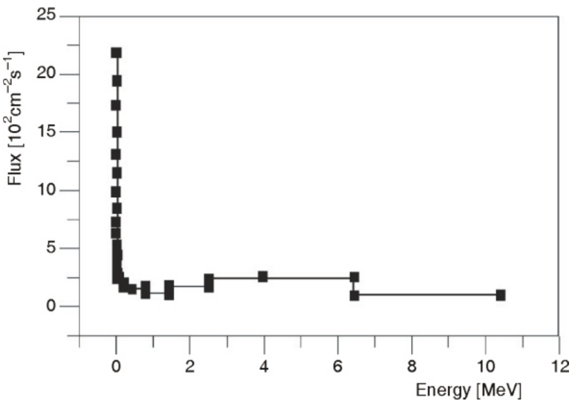


**Figure 6. Neutron flux density as a function of energy in the point B (*r* = 100 cm, *h* = 70 cm)**

where $\dot{D}_{\gamma}$ is given in grays per hour (Gy/h), and $P$ is given in watts (W).

Hard disks set at the center of HERBE system, had the absorbed gamma dose rate $\dot{D}_{\gamma}$ = 0.23 Gy/h.

For hard disks at the periphery of HERBE system, the gamma dose rate was determined based on the dependency [12]

$$\dot{D}_{\gamma} \quad 4.03772 \; 10^{\;3} P^{0.989173} \qquad (2)$$

and it amounted to $\dot{D}_{\gamma}$ = 0.039 Gy/h.

In the case of hard disks covered with Cd, as already stated, the absorbed neutron dose rate decreased, while the absorbed gamma dose rate slightly increased. The influence of Cd onto the increase of gamma dose rate is insignificant, since it is smaller than the error used to obtain data from a calibration curve, *i. e.*, from a fitted formula (2), and was also $\dot{D}_{\gamma}$ = 0.039 Gy/h. Functional examinations of all irradiated magnetic memories show no change in their content, *i. e.*, that they suffered no functional damages. It is for the fact that the neutron dose rates, and thus the entire absorbed doses, are relatively small. Not even the increase of the reactor power to the maximum of $P$ = 45 W has brought about any changes in their functionality. Thus, considering the damage caused in domain structures it is necessary to work with reactor powers of the least order of MW.

## Semiconductor memories (EPROM, EEPROM)

The effects of gamma radiation have been considered as a relative differential change of a number of faults with absorbed radiation dose and relative cumulative changes of number of faults with absorbed radiation dose.

Relative differential change of the number of faults with absorbed radiation dose, for the examined EPROM samples, is shown in fig. 7. Relative cumulative change of number of faults (in percentages) with absorbed radiation dose, for the examined EPROM samples is shown in fig. 8. The obtained values, shown in graphs, are their average result values obtained by examining 20 commercial components.

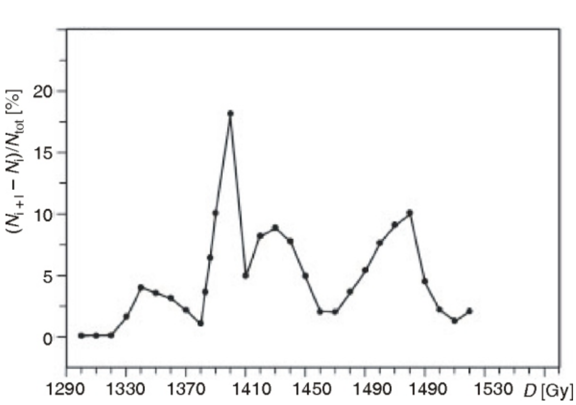


**Figure 7. Average relative differential change of number of faults with absorbed dose in irradiated EPROM samples ($N_{tot}$ = 512 bits, $N_0$ = 0)**

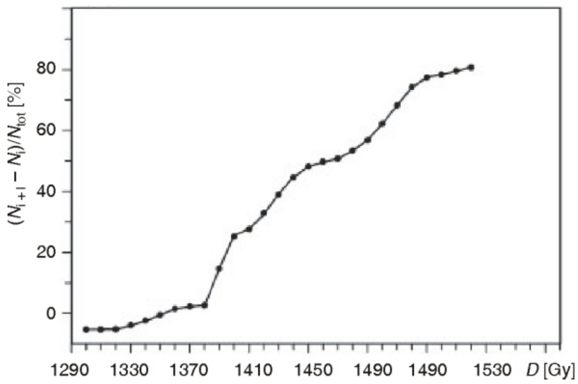


**Figure 8. Average relative cumulative change of number of faults with absorbed dose in irradiated EPROM samples ($N_{tot}$ = 512 bits, $N_0$ = 0)**

As we can conclude from figs. 7 and 8, ionizing gamma radiation $^{60}$Co brings to content damages of EPROM components. The first changes appear for doses at about 1320 Gy. The changes are the most visible for doses at about 1400 Gy. Those changes are of reversible character and after deleting the initial content and reprograming the memory, all EPROM samples have been 100 % functional again, and we have written new contents of the logical state "1", and they have been re-exposed to the $^{60}$Co gamma radiation.Due to acumulative nature of gamma radiation, a sensitivity level is then much lower, as it is shown in figs. 9 and 10. We see that the first changes now appear for the doses at about 100 Gy. The changes are the most expressed for the doses at about 200 Gy. The entire absorbed radiation dose, both from natural and artificial resources, causes cumulative damage effects, creating positive and negative carriers. It is firstly a surface leaking phenomena that is reflected in the gate and/or in the oxide field.

The main effect the ionizing gamma radiation produces in EPROM components is a generation of carriers, *i. e.*, creation of electron-hole pairs by breaking Si – O connections in $SiO_2$. This leads to a formation of captured positive carriers (holes) in insulator and concentration of captured negative carriers in in-

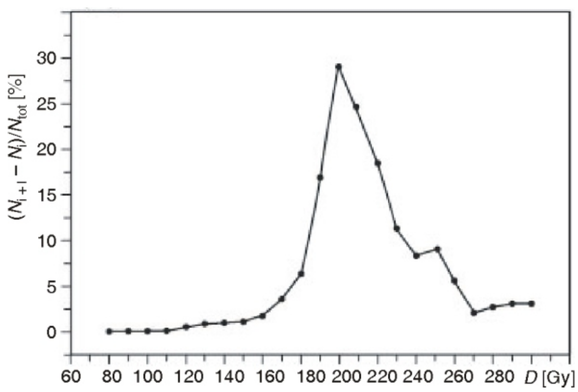


**Figure 9. Average relative differential change of number of faults with absorbed dose in reprogrammed and repeatedly irradiated EPROM samples ($N_{tot}$ = 512 bits, $N_0$ = 0)**

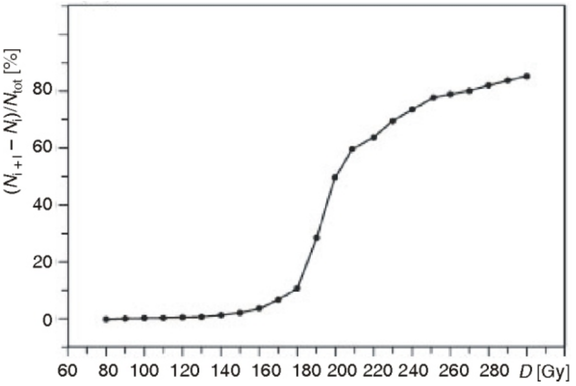


**Figure 10. Average relative cumulative change of number of faults with absorbed dose in reprogrammed and repeatedly irradiated EPROM samples ($N_{tot}$ = 512 bits, $N_0$ = 0)**

sulator-channel interface. Electrons, more mobile than holes, even at the room temperature, leave the oxide quickly. Holes, on the other side, being less mobile, remain trapped in the oxide and contribute to creation of a positive charge in the oxide $Q_{ox}$. The charge $Q_{ox}$ is proportional to the oxide layer thickness $t_{ox}$, thus the resulting change of the threshold voltage is [13]

$$\Delta V_{th} \quad \frac{Q_{ox} t_{ox}}{\varepsilon_{ox}} \tag{3}$$

while the connection between the threshold voltage and the total dose is given in eq. [14]

$$\Delta V_{th} \quad \frac{\alpha q m_v t_{ox}^2 D}{w \varepsilon_{ox}} \tag{4}$$

where $w$ is the effective energy value needed for the production of pairs in the oxide and it is $w$ = 18 eV, $m_v$ – the density mass of the oxide, $\alpha$ – a parameter depending of technological conditions, and $\varepsilon_{0x}$ – the dielectric constant of the oxide.

The second important factor gamma radiation leads to in EPROM components is a formation of surface conditions in $Si/SiO_2$ interfaces. Different from oxide charges that are always positive, surface conditions are amphoteric and capture electrons in *n*-channel components, leading to increase of the threshold voltage. The second type of traps, so-called "border traps", is located in the oxide, very near to $Si/SiO_2$ interface, and they also capture electrons. Also, the oxide charges contribute to creation of additional traps in the border surfaces [15].

Relative differential change of a number of faults with absorbed dose in irradiated EEPROM samples is shown in fig. 11. Relative cumulative change of number of faults with absorbed dose in irradiated EEPROM samples is shown in fig. 12. The obtained values, shown in graphs, are the average result values, gained from 20 examined commercial components.

From figs. 11 and 12, it is seen that the first fault appears at the doses of 1100 Gy. With the increase of

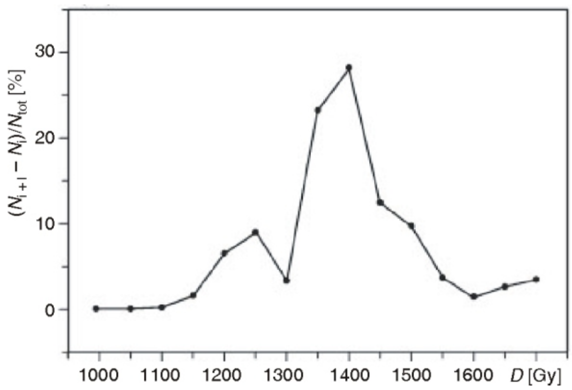


**Figure 11. Average relative differential change of number of faults with absorbed dose in irradiated EEPROM samples ($N_{tot}$ = 128 bits, $N_0$ = 0)**

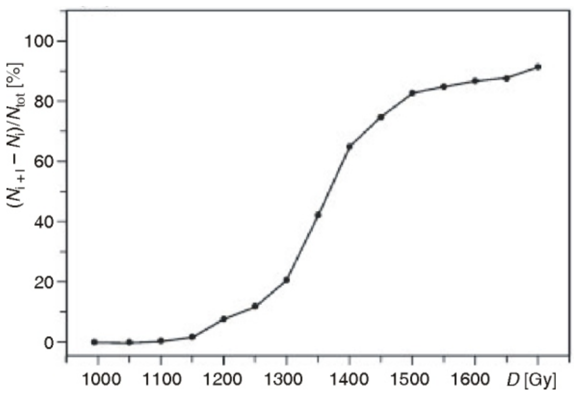


**Figure 12. Average relative cumulative change of number of faults with absorbed dose in irradiated EEPROM samples: ($N_{tot}$ = 128 bits, $N_0$ = 0)**

the absorbed dose, the faults number increases, *i. e.*, the functionality of EEPROM components decreases. It should be emphasized that those changes are of irreversible character, different from the ones of EPROM components that can be reprogrammed after deleting them by means of ultraviolet rays.

As we have previously emphasized, the main effect that gamma radiation $^{60}Co$ causes is generating electron-hole pairs in $SiO_2$ gate insulator. The number of generated electron-hole pairs depends on the material and available volume. A part of electron-hole pairs is recombined. What will be a number of recombined electron-hole pairs depends on the electric field in an irradiated oxide [16]. The stronger the field, the higher number of pairs will avoid recombination. Mobile electrons, under the influence of the applied voltage at the gate, leave the oxide insulator quickly. Immobile holes will be either trapped in the oxide or will drift under the influence of the electric field on the floating gate. They contribute to formation of a positive oxide charge. A part of holes that is not trapped in the oxide is injected into the floating gate, reducing number of electrons in it, and thus conditioning the decrease of the threshold voltage.

Therefore, generating of the electron-hole pairs leads to capturing of positive carriers (holes) in the insulator and capturing negative carriers, concentrated at the insulator-channel interface [17]. Negative gate voltage demands accumulation of positive carriers at $Si/SiO_2$ surfaces. Positive carriers, induced by the ionizing radiation,govern the increase of negative gate voltage, to compensate the positive charge. Thus,hole trapping effect and the effect of injected holes, under the radiation influence, lead to decrease of the threshold voltage. Both of these effects are also reduced with the reduction of the oxide thickness [18]. Most of the oxide vacancies appear near the oxide/substrate and oxide/floating gate interfaces. Positive charges of trapped holes have a tendency to mask negative charge at the gate, and it leads to decrease of FG transistor threshold voltage.

The third mechanism that appears during irradiation of EEPROM is electron emission through the floating gate/oxide barrier. The emission is responsible for deleting parts of EEPROM, under the influence of ultraviolet light. During exposure to this light, EEPROM will also lose its charge. Under the influence of gamma radiation, photons of sufficient energy will cause electron emission from a potential barrier [19]. Also, the electron in oxide will be moved quickly onto the substrate or a control gate, under the influence of the electric field. The electron loss also leads to decrease of the threshold voltage. On the other side, electron emission does not lead to reduction of the oxide thickness.

The threshold voltage can be quantitatively expressed in the following way

$$V_{\mathrm{T}} \quad V_{\mathrm{T0}} \quad \frac{q_{\mathrm{s}} d}{\varepsilon} \tag{5}$$

where $V_{T0}$ is an initial threshold voltage of a transistor, $q_s$ – the density of surface charges at the gate, $d$ – the oxide thickness between a control and floating gate, and $\varepsilon$ – the dialectic constant of the oxide.

Therefore, based on the previous discussion, it can be concluded that there are three primary mechanisms appearing during EEPROM gamma irradiation, namely: hole trapping in the oxide, injection of holes from the oxide layers, and electron emission through the floating gate/oxide barrier.

For relatively small values of electric field in memories, the trapping of holes and their injection can be presented with the function [20]

$$f(E) \quad 1 \quad e^{kE} \quad kE \tag{6}$$

for $E$ 0,5 mV/cm.

In the case of a high level ionizing radiation, *i. e.,* huge absorbed doses, these three processes will be balanced, and will be characterized by a balanced threshold voltage $V_{TE}$. In addition to these processes, under the influence of gamma radiation, there is a formation of surface conditions at $Si/SiO_2$ interface, that are insignificant compared to the stated effects.

The contribution of effects induced by radiation is a complex function of material and insulator gate thickness as well as a processing method and doping of the insulator gate at the surface of Si.

This is a reason that a number of damaged locations in the examined memories varies. It can be concluded that statistical fluctuations of faults number of the examined samples are the consequence of a difference in an oxide layer volume. If an active oxide layer volume is very small, significant fluctuations of the absorbed dose are detected.

## CONCLUSIONS

In this paper, the results of examination of radiation hardness of commercial magnetic (Toshiba MK4007 GAL) and semiconductor (AT 27C010 EPROM and AT 28C010 EEPROM) components are presented. The paper has also established a high radiation hardness of magnetic memories in the $(n, \gamma)$ radiation field. By examining radiation hardness of EPROM and EEPROM components, it has been shown that gamma radiation leads to their damaging. It has been obtained that the first faults within EPROM components appear for the absorbed radiation doses at about 1320 Gy, and with EEPROM components, for the doses at about 1100 Gy. It has been shown that damages within EEPROM are irreversible and lead to their permanent non-functionality. The damages within EPROM are reversible and they can be used again after deleting and reprogramming. Afterwards, their threshold radiation sensitivity is more than 10 times smaller, and the first faults appear within absorbed doses at about 100 Gy. The obtained results have been theoretically explained and they are significant for application of these components, and reliability of their functioning in specific conditions, where the work in the field of radiation also belongs to.

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## AUTHORS' CONTRIBUTIONS

Theoretical analysis was carried out by I. S. Fetahović and E. Ć. Dolićanin. Experiments were carried out by I. S. Fetahović and B. B. Lončar. All of the authors have analyzed and discussed the results. The manuscript was written by I. S. Fetahović. The figures were prepared by N. M. Kartalović.

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## ПОУЗДАНОСТ РАДА РАЧУНАРСКИХ МЕМОРИЈА У РАДИЈАЦИОНОМ ОКРУЖЕЊУ

У раду су приказани резултати испитивања радијационе отпорности рачунарских магнетних (Toshiba MK4007 GAL) и полупроводничких (AT 27C010 EPROM и AT 28C010 EEPROM) меморија у пољу радиоактивног зрачења. Магнетне меморије испитиване су у пољу неутронског, а полупроводничке у пољу гама зрачења. Добијени резултати показали су високу радијациону отпорност испитиваних магнетних меморија. С друге стране, утврђено је да су полупроводничке меморије знатно осетљивије и да радиоактивно зрачење може да доведе до значајног оштећења њихове функционалности.

*Кључне речи: магнетна меморија, полупроводничка меморија, радиоактивна отпорност, гама зрачење, неутронско зрачење*