THE INFLUENCE OF NEUTRON AND GAMMA RADIATION ON THE RELIABILITY OF MAGNETIC AND SEMICONDUCTOR MEMORIES

by

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The miniaturization of computer facilities conditioned by the miniaturization of applied components makes them very sensitive to radioactive radiation. This is where neutron and electromagnetic radiation come to the fore. The reason for the particularly pronounced effects of this radiation is the fact that they do not interact with the Coulomb force, so they pass (leave) the reactor vessel unimpeded. This study examines the reliability of magnetic and semiconductor computer memories in the field of neutron and gamma radiation. This study experimental, and conducted under well-controlled conditions. The combined measurement uncertainty of the experimental procedure is less than 5 %. Sophisticated methods of mathematical statistics were used to process the stochastic results of measurements.

Key words: operational reliability, neutron radiation, gamma radiation, magnetic memory, semiconductor memory

INTRODUCTION

What makes neutron and gamma radiation different from other types of radiation is that they are non-electric. As a result, these two types of radiation (generated in the fission reactor) easily pass through the protective Coulomb fields and contaminate the environment of the fission reactor. Contamination of the fission reactor environment with neutron and electromagnetic radiation leads to serious problems with control computer systems that have become extremely sensitive to this type of radiation due to the miniaturization of their components [1, 2].

The basic types of radiation damage, destructive and transient, can be divided into: effect of total absorbed dose [3, 4], point gamma effect [5, 6], single-event error or single-event upset (which is also called soft error) [7-9], neutron effects that cause memory damage depending on the neutron energy, and electromagnetic pulse effects that occur due to the high-energy electromagnetic pulses [10, 11].

According to the method of data storage, computer memories can be divided into three basic groups: magnetic, semiconductor, and optical. Magnetic memories are magnetic disks, drums, and tapes. For magnetic memories, information is recorded in binary form. The states "0" or "1" correspond to the states of the remanent magnetic induction of the opposite orientation [12]. Semiconductor memories are divided into bipolar and metal oxide semiconductor (MOS) memories. In recent times, MOS memories are mainly used [13-15]. In this study, the influence of neutron and electromagnetic radiation on the optical type of memories will not be considered, since it is negligible [16].

This study aims to examine the influence of neutron radiation on magnetic memories and the influence of electromagnetic radiation on MOS memories of EPROM and EEPROM types using an experimental procedure that is similar to the real operating conditions of a fission reactor. Such a choice is logical since magnetic memories are sensitive exclusively to neutron radiation, while MOS-type memories are almost exclusively sensitive to electromagnetic (gamma) radiation [17, 18].

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INFLUENCE OF NEUTRON AND GAMMA RADIATION ON MAGNETIC MEMORIES AND SEMICONDUCTOR MOS-TYPE MEMORIES

Neutron damage to the atomic structure is most often of an irreversible type. This particularly applies to magnetic memories. The MOS memories are used almost exclusively as semiconductors. In MOS-type semiconductor memories, neutron effects are much less expressed than gamma radiation effects [19]. The MOS-type semiconductor memories can be divided into two main groups: random-access memory (RAM) where reading and entering content is enabled, and Read-only memory (ROM) enables saving and reading of content.

When considering the problem of neutron shielding, one should consider the fact that the effective absorption cross-section of neutrons has an inverse dependence on their speed. The problem of neutron shielding takes place in three steps: slowing down of fast neutrons, capture of slowed down neutrons, and attenuation of gamma radiation caused by neutron activation of the shielded material [20, 21]. Slowing down is the process of capturing fast neutrons which is most effectively achieved by a combination of water (moisture) and cadmium. This is how the experiment was carried out in this study as well.

Electromagnetic radiation that can cause functional or destructive damage to MOS-type semiconductor components is gamma and X-radiation. Functional or destructive damage of semiconductor components by electromagnetic radiation occurs with the material through three basic types of interaction: photoelectric effect, Compton scattering, and electron-hole pair production. All these effects lead to functional and/or destructive damage to semiconductor memory components.

PROCEDURE FOR MEASURING THE EFFECTS OF NEUTRON AND ELECTROMAGNETIC RADIATION ON MAGNETIC AND SEMICONDUCTOR MEMORIES OF THE MOS-TYPE

Magnetic memory disks (BASF 1.44", floppy disk, dimensions $L = H = 90$ mm; $d = 3$ mm) were irradiated in the Vinča Institute of Nuclear Sciences. One diskette was placed in the center of the reactor system (cylindrical in shape, height $H_{\max} = 140$ cm and diameter $2r_{\max} = 40$ cm), and the other two disks were on the periphery. One of the floppy disks placed on the periphery of the reactor was coated with wet cadmium.

The calculation of the spatial distribution of the flux and the maximum energy doses was performed with the program VEGA [22]. The density of gamma photons generated from fission fragments was determined experimentally. The absorbed dose on the lateral side of the fission reactor was determined in this way. Figure 1 presents the time dependence of the gamma radiation energy level on the exoatmospheric and endoatmospheric sides. The energy rate is expressed in terms of million electron volts per second per kiloton of explosion energy.

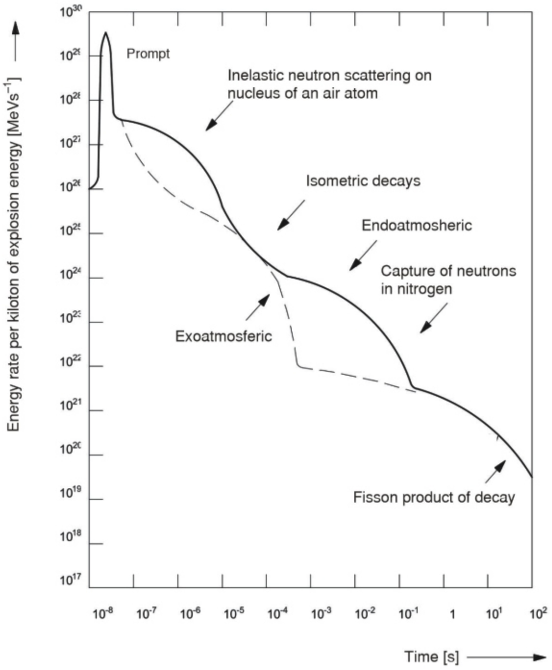

Figure 1. Time dependence of the energy level of gamma radiation on the exoatmospheric and endoatmospheric side [23]

Before the neutron irradiation of the magnetic memory disks, which were placed two on the periphery and one in the center of the HERBE, the binary content 1010 was written into them [22]. After the irradiation, which lasted for 0.5 hours at a reactor power of 10 W, the binary content was read to determine the number of locations where the content changed, *i. e.*, the number of locations that experienced reversible damage.

Irradiation of EPROM and EEPROM memory components was performed with a calibration device at the Vinča Institute of Nuclear Sciences, fig. 2.

Groups of five samples of EPROM and EEPROM memories were examined in the ^{60}Co gamma radiation field. Tests were performed on JL 27C512 EPROM memories (product of TMS company, Texas) and 28C64 EEPROM memories. The 28C64C EEPROM memories (product of STMicroelectronics company, Geneva, Switzerland) belong to the group of Complementary Metal-Oxide-Semiconductor (CMOS) components that have an oxide nitride dielectric in floating gate (FG) memory transistors [24]. The tested semiconductor memories were new. Further, it tested groups of five samples of EPROM and EEPROM memories that had not been used for two years [25, 26]. The goal of having two groups of samples examined two years apart was to establish the eventual effect of short aging. All samples were tested for statistical identity with the U-test and Chauvenet's criterion test [27, 28].

Before the start of irradiation, the same memory content was written (recorded) in all memories. Con-

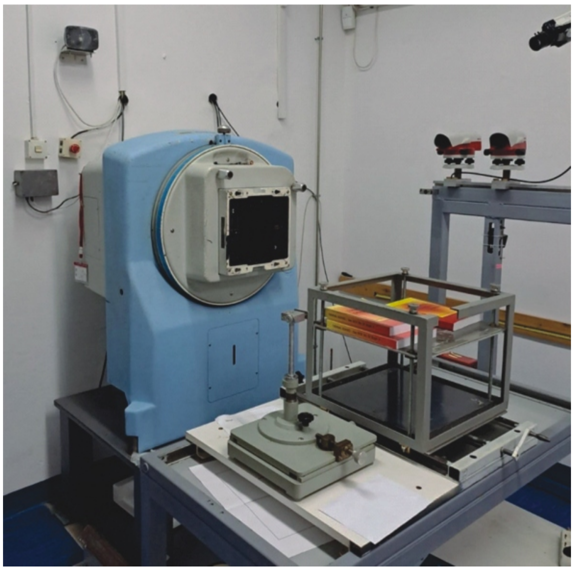

Figure 2. Calibration device (implementing the gamma field)

stant voltage pulses were used for this purpose. The dimensions of the radiation field were 8 cm 8 cm. The distance between the source and the radiation test field was 45.6 cm. The strength of the absorbed dose in the air was 60 Gyh^{-1} and 65.82 Gyh^{-1} in the silicon. As these tests were performed again after two years, the activity of the source was lower, so a correction was made by changing the distance between the ^{60}Co source and the memory (target).

The total absorbed dose was taken as a variable observation parameter. From the first observed changes in the memory record, the dose was increased in small steps, to see the changes as clearly and precisely as possible. The total absorbed dose produces cumulative damage effects creating negative and positive carriers. It is primarily a surface leakage phenomenon, reflected at the gate and affecting the field in the oxide.

A memory programming environment was Marconi Applied Technologies 512 programmer [13] with a unique originally developed Pascal program. Erasing the contents of EEPROM components (which were not functionally irreversibly damaged) was performed electrically. Erasing the contents of the EPROM components was performed with a standard UV eraser. All EEPROM memories suffered irreversible changes so it was not possible to reprogram them, *i. e.*, write the memory contents into them.

The effects of irradiation were observed as differential changes and as cumulative changes in the number of defects as a function of the total received radiation dose.

RESULTS AND DISCUSSION

To examine the effect of neutron radiation, the energy limits of the neutron spectrum were divided into four groups as shown in tab. 1.

Table 1. Energy limits used in testing neutron radiation

Group	Lower limit [MeV]	Upper limit [MeV]
1-a	$8\cdot10^{-1}$	$1.05\cdot10^{1}$
2-b	$4.65\cdot10^{-3}$	$8\cdot10^{-1}$
3-c	$4.65\cdot10^{-7}$	$4.65\cdot10^{-3}$
4-d	$1\cdot10^{-9}$	$4.65\cdot10^{-7}$

Based on the VEGA program [22], the dependence of the neutron flux density for the memory (floppy) disk at a height of *h* = 70 cm was determined depending on *r* [cm] for all four energy groups, which is shown in fig. 3.

Figure 4 shows the dependence of the neutron flux density for the memory (floppy) disk on the height *h* [cm] for the value *r* = 20 cm.

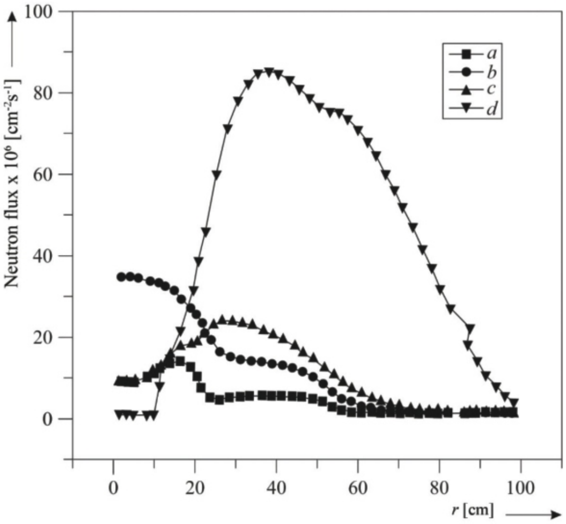

Figure 3. Neutron flux density for the memory (floppy) disk depending on *r* [cm] at the height *h* = 70 cm for all four energy groups [22]

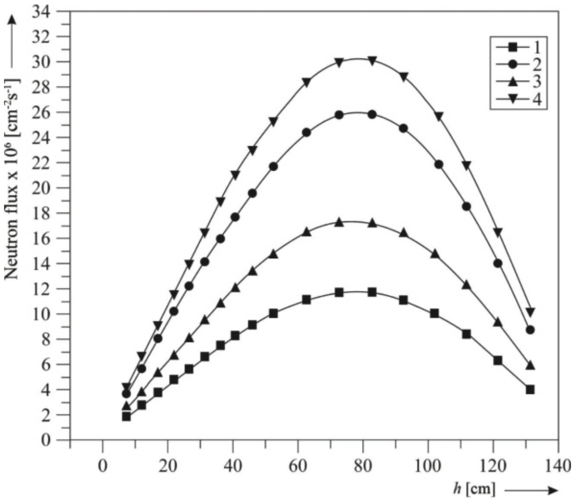

Figure 4. Neutron flux density for the memory (floppy) disk as a function of *h* [cm] at *r* = 20 cm for all four energy groups [22]

Figure 5 shows the dependence of neutron flux density on energy in the center of the HERBE (r = 20 cm, h = 70 cm).

Based on that, the total strength of the absorbed dose was calculated as the sum of the strength of the absorbed doses for all four energy groups at the given point, and it amounted to 4.58 $\mathrm{Gyh^{-1}}$. In the same way, the dependence of the neutron flux density was determined for the memory (floppy) disks placed on the borders of the reactor vessel.

Figure 6 shows the neutron flux density depending on the height h [cm] at r = 10 cm for the first three energy groups (both floppy disks on the periphery of the system were covered with wet cadmium for unused samples two years old).

Figure 7 shows the dependence of neutron flux density on energy at r = 100 cm and h = 70 cm. In this case, the diskettes (floppy disks) were located in the same place as in the previous case, but they were covered with wet cadmium that absorbed low-energy neutrons of the fourth group so that the total absorbed dose was affected only by neutrons of the first three energy groups.

Although the tested diskettes received significant doses of gamma radiation in addition to neutron doses, fig. 1, during the irradiation there was no change in the memory content. This can be explained by the large thickness of the domain boundaries (on the order of μm), so the total absorbed energy is not sufficient to destroy them.

The effect of gamma radiation on semiconductor memories is significant. Figure 8 shows the differential change in the number of defects (errors) N [bits] depending on the total dose D of gamma radiation of all five EPROM memories irradiated for the first time.

Figure 9 shows the cumulative change in the number of defects (in percent) depending on the total dose of gamma radiation of all five EPROM memories irradiated for the first time where $N_0 = 0$.

As can be concluded from fig. 9, gamma radiation leads to damage to the contents of EPROM memories. The first changes in the contents of EPROM memories were registered at doses around 1200 Gy (that value represents the threshold of the effect of gamma radiation on semiconductor memories, hereinafter only the threshold). The changes were reversible and after erasing the initial content and reprogramming all the EPROM samples were 100 % functional again, and new content was written (recorded) into them and the samples were again exposed to gamma radiation. Due to the cumulative effect of radiation, the sensitivity level was much lower. It was observed that the first effects on re-irradiated samples occurred at doses (threshold) of 80 Gy.

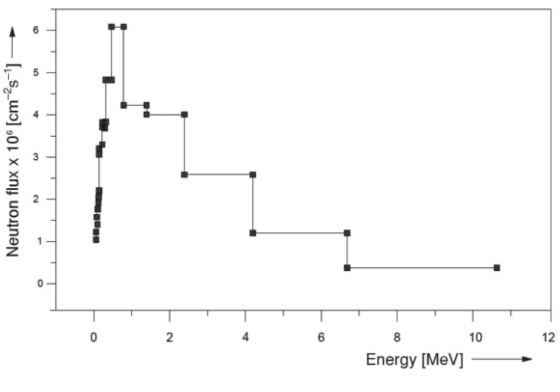

Figure 5. Dependence of neutron flux density on energy in the center of the HERBE (r = 20 cm, h = 70 cm) [22]

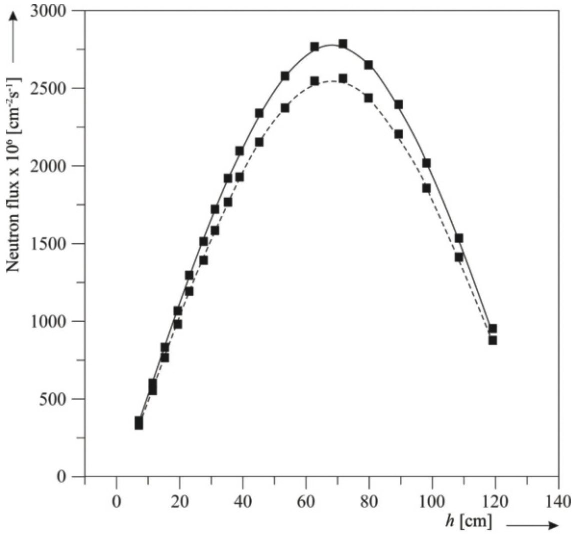

Figure 6. Dependence of the neutron flux density depending on the height h [cm] at r = 10 cm for the first three energy groups; new samples not covered with wet cadmium, first measurements; - - - - unused samples two years old covered with wet cadmium [22]

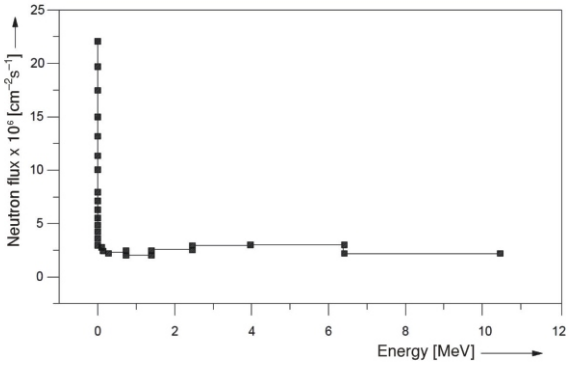

Figure 7. Dependence of neutron flux density on energy at r = 100 cm and h = 70 cm [22]

The main effect that results from the action of ionizing gamma radiation in EPROM memories is the generation of charge carriers, *i. e.*, the creation of electron-hole pairs by breaking the Si-O bonds in the SiO_2 layer. This leads to the creation of affected cavities in the insulator and the concentration of electrons on the insulator-channel boundary surface. Electrons, being much more mobile than holes, leave the oxide faster.

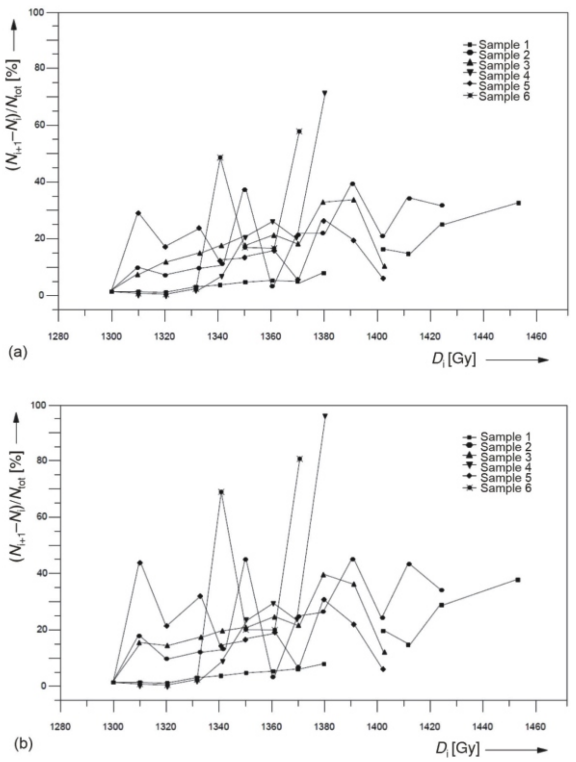

Figure 8. Differential change in the number of defects depending on the total dose of gamma radiation of all five EPROM memories irradiated for the first time; (a) new samples, first measurements and (b) unused samples two years old

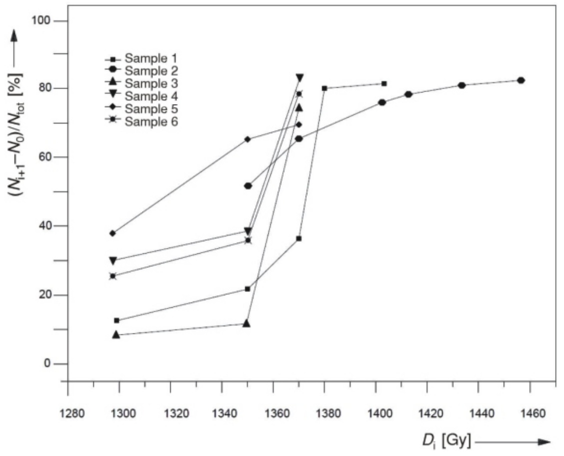

Figure 9. Cumulative change in the number of defects [%] depending on the total gamma radiation dose of all five EPROM memories

The weakly mobile cavities remain trapped in the oxide and contribute to the creation of a positive charge of the oxide Q_{ox}. These captured positive charges are the cause of the negative shift of the I_D-V_G characteristics. The charge Q_{ox} is proportional to the thickness of the oxide layer t, so the resulting threshold voltage shift V_{th} is

$$V_{th} \quad \frac{Q_{ox} t_{ox}}{\varepsilon_{ox}} \tag{1}$$

where ε_{ox} is the dielectric constant of the oxide.

The relationship between the threshold voltage and the total dose is

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

where ω is the effective value required to produce an electron-hole pair in the oxide with the value of 18 eV, m_v – the mass volume of the oxide, q is a charge, and – the a parameter that depends on the technological conditions.

Another important effect caused by gamma radiation of EPROM memories is the formation of surface states on Si-SiO$_2$ interfaces. In contrast to oxide charges, which are always positive, surface states in amorphous materials capture an electron in the component's N-channels, which leads to an increase in the threshold. Further, another type of trapping (boundary captures) located in the oxide very close to the Si-SiO$_2$ interface also captures electrons. Also, oxide charges contribute to the formation of captures on the boundary surfaces.

Figure 10 shows the differential change in the number of defects depending on the total absorbed dose of gamma radiation of all five tested EPROM memories.

Based on the obtained results shown in fig. 10 and the corresponding results of the cumulative change in the number of defects depending on the total absorbed dose of gamma radiation for all tested memories, it can be concluded that the threshold occurs at doses of 1000 Gy. With an increase in the total dose, the number of errors also increases, but the functionality of EEPROM components decreases. It should be

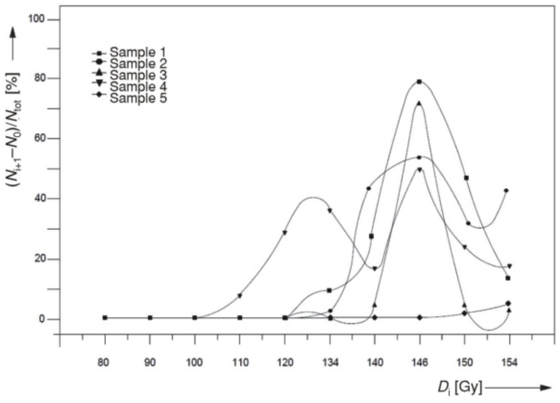

Figure 10. Differential change in the number of defects depending on the total absorbed dose of gamma radiation of all five tested EEPROM memories; (a) new samples, first measurements and (b) unused samples two years old

emphasized that these changes are irreversible, unlike those of EPROM components.

As already pointed out, the main effect caused by gamma radiation on MOS-type semiconductor memories is the generation of electron holes in the SiO_2 gate insulator. The number of generated electron-hole pairs depends on the material and the available volume. Part of the electron-hole pairs recombine. The proportion of electron-hole pairs that will be recombined depends on the strength of the electric field in the oxide. The stronger the field, the more pairs that will avoid recombination. Under the influence of the applied voltage on the gate, the mobile electron quickly leaves the oxide of the insulator. Hard-to-move cavities become trapped in the oxide or drift under the influence of the electric field on the floating gate. They contribute to the formation of the positive charge of the oxide. The part of the cavities that are not blocked in the oxide is injected into the floating gate and reduces the number of electrons in it, thereby causing the threshold to be lowered.

Therefore, the generation of electron-hole pairs leads to the capture of positive carriers in the insulator and the capture of negative carriers concentrated on the insulator-channel boundary surface. The negative gate voltage requires the accumulation of positive carriers on the $Si\text{-}SiO_2$ surfaces. The positive carriers induced by the action of gamma radiation cause an increase in the negative gate voltage to compensate for the positive charge. Thus, both the effects of cavity capture and the effects of cavity injection under the influence of radiation lead to a decrease in the threshold. The influence of both effects on the threshold voltage also increases as the oxide thickness decreases. Most oxide voids occur near the oxide-substrate and oxide-floating gate interfaces. The positive charges of the trapped cavities tend to mask the negative charge on the gate. This causes the threshold voltage of the transistor to decrease.

The third mechanism that occurs during the effect of radiation on EEPROM memories is the emission of electrons through the floating gate-oxide barrier. This emission is responsible for erasing parts of the contents of EEPROM memories under the influence of ultraviolet light. When exposed to ultraviolet light, the EEPROM will also lose its charge. Under the influence of gamma radiation, photons of higher energies eject electrons through the potential barrier. In this way, the electrons in the oxide will be quickly transferred to the substrate or the control gate. This loss of electrons leads to a decrease in the threshold voltage.

The threshold voltage can be expressed as

$$V_{\mathrm{T}} \quad V_{\mathrm{T0}} \quad \frac{\mathrm{d} q_s}{\varepsilon} \tag{3}$$

where V_{T0} is the initial threshold voltage, q_{s} – the gate surface charge density, d – the thickness of the oxide between the control and floating gate, and ε – the dielectric constant of the oxide.

Based on this, it can be concluded that three basic mechanisms occur when the EEPROM memory is exposed to gamma radiation: cavity capture in the oxide; injection of cavities from oxide layers; and electron emission through the floating gate-oxide barrier. In the case of high levels of ionizing radiation, these three processes are balanced. In addition to these processes, during the effect of gamma radiation on MOS-type memories, the formation of surface states occurs at the $Si\text{-}SiO_2$ boundary surfaces, but it is shown that these states are negligible in the overall effect of gamma radiation.

CONCLUSIONS

A detailed examination of the effects of neutron and gamma radiation on computer memories is extremely important for the reliable operation of nuclear fission reactors. The most important conclusion is that it is advisable to use magnetic memory when the conditions permit. Furthermore, it can be claimed that magnetic memories are completely resistant to neutron and gamma radiation. These two radiations are the main radioactive contaminants in the vicinity of the fission reactor.

Semiconductor memories are extremely sensitive to the effects of gamma radiation. The analysis of the obtained results led to the conclusion that the effect of gamma radiation on MOS-type memories can be reduced. However, this reduction could be greatly improved by the method of multiple redundancy of semiconductor memory components. It can be argued that this is a direction in which further research should be pursued. The final success of such a procedure can be achieved by the introduction of nanotechnologies, which will result in practically infinite redundancy.

It should be emphasized that neither magnetic nor semiconductor memories showed any effect of aging for two years because that is a short period. The physical mechanisms of memorization in the case of MOS-type semiconductor memories indicate that their aging can be expected for longer periods. For magnetic memories, there is no theoretical basis to expect an aging effect in real time.

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AUTHORS' CONTRIBUTIONS

N. M. Kartalović gave the idea for the experiment which was carried out by U. D. Kovačević, D. P.

Nikezić, and P. V. Osmokrović. All the authors analyzed the results and participated in the preparation of the final version of the manuscript under the supervision and guidelines of N. M. Kartalović and P. V. Osmokrović.

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УТИЦАЈ НЕУТРОНСКОГ И ГАМА ЗРАЧЕЊА НА ПОУЗДАНОСТ МАГНЕТНИХ И ПОЛУПРОВОДНИЧКИХ МЕМОРИЈА

Минијатуризација компјутерских постројења условљена минијатуризацијом примењиваних компоненти чини их врло осетљивим на радиоактивно зрачење. Ту посебно долази до изражаја неутронско и електромагнетно зрачење. Разлог за посебно изражене ефекте овог зрачења је чињеница да не интерагују Кулоновом силом тако да пролазе (тј. излазе) из реакторске посуде несметано. Ова студија испитује поузданост магнетних и полупроводничких рачунарских меморија у области неутронског и гама зрачења фисионог реактора. Такође, студија је експерименталног карактера рађена под добро контролисаним условима. Комбинована мерна несигурност експерименталног поступка је била мања од 5 %. За обраду стохастичких резултата мерења коришћене су софистициране методе математичке статистике.

Кључне речи: поузданост рада, неутронско зрачење, гама зрачење, магнетна меморија, полупроводничка меморија