MONTE CARLO OPTIMIZATION OF REDUNDANCY OF NANOTECHNOLOGY COMPUTER MEMORIES IN THE CONDITIONS OF BACKGROUND RADIATION

by

Edin Ć. DOLIĆANIN and Irfan S. FETAHOVIĆ *

State University of Novi Pazar, Novi Pazar, Serbia

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The aim of this paper is applying statistical laws and enlargement law to determine a redundancy level of nanotechnology computers with a pre-given statistical confidence. We have tested radiation hardness of MOS memory components (commercial EPROM memory) using both Monte Carlo simulation method and experimental procedure. Then, by using the statistical enlargement law, we have performed the analysis of redundancy optimization of MOS structure for nanotechnology computers, under the influence of background radiation, and obtained more than satisfying results.

Key words: nanotechnology computer memory, optimization, redundancy, Monte Carlo simulation, radiation

INTRODUCTION

A higher level of miniaturisation of electronic components, with an increased electromagnetic contamination of the environment and always present secondary cosmic radiation, significantly reduce the reliability of work of such components. This is especially visible in manufacturing nanotechnology computers. As any solution which implies shielding would make miniaturization meaningless, it is thus inappropriate. In practice, there is a tendency to apply redundancy of memory and other systems. However, redundancy in nanotechnology, besides a low price, has an issue of a significant cost increase in terms of energy consumption, both active one and energy needed for cooling. For this reason, it is necessary to optimise redundancy level, to achieve maximum reliability of nanotechnology computers.

This is the very aim of the paper, *i. e.* by applying statistical laws and enlargement law, to determine a redundancy level of nanotechnology computers, with a pre-given statistical confidence [1-5].

In the centers of stars, there are huge amounts of high-energy subatomic particles. In some cases, these processes create an extremely strong electromagnetic radiation. In this way, the intergalactic space is filled with photons and all types of mass particles, and it can be considered as dense plasma (because of huge mega-galactic distances). Most mass particles are protons with energies significantly higher than energies generated in the most powerful accelerators. When these highly energetic rays from cosmos (so-called a primary cosmic radiation) reach the atmosphere, they collide with the nuclei of atmospheric air molecules and create a number of different particles (so-called a secondary cosmic radiation). In this way, the real showers of subatomic particles originate [5].

These showers of the secondary cosmic radiation influence all electronic components. This influence is higher if a level of miniaturisation of the observed component is higher. In this paper, a special attention shall be given to MOS memory components [Appendix].

Since the characteristics of most MOS devices depend significantly on the lifetime of minority carriers, they are relatively insensitive to displacement damages, caused by displacing atoms from the lattice. Although it is possible to notice an increase of leaking current in interfaces of radiated MOS transistors, and also certainly displaced atoms' influences during the individual ions passing through MOS structures of small dimensions, generally, displacement damages within MOS are of a secondary importance. While exposing MOS structure to the ionizing radiation, the most significant change causes ionization in oxide (SiO_2) and in the semiconductor (S_i). The width of the energy gap of silicon dioxide and silicone is 9 eV and 1.1 eV, respectively. In nano-layered MOS structure,

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

ionization generated electron-hole pairs lead to a noise that is significantly higher (several orders of magnitude) than a useful signal [7-9].

THE STATISTICAL ENLARGEMENT LAW

Content disturbance in a semiconductor memory as a result of background radiation happens due to ionization of a semiconductor or insulation structure. Since it is a random process, it is described by a distribution function of the appropriate variable. However, if the observed structures are big (*i. e.*, made of a large number of redundant identical memories), the disturbance of the content can be developed in parallel, both in space and time. For practical reasons, in that case, there is a tendency of determining a distribution function of the appropriate variable of an individual memory, and the final statistics of the reliability of the entire memory system is derived based on the enlargement law [10-13].

The statistical enlargement law represents a practical implementation of the multiplication law for independent variables. Of course, within it, it is necessary to adopt a mutual independence of ionization effects in individual memories. In a case of multi-redundant structures of nanocomputers, this assumption is justified, where the ionization effects on components that are physically close must be neglected. If p_1 is a probability that a background radiation leads to ionization within one memory unit of a redundant memory system, the probability of a content error in the entire memory system is

$$p_{\mathrm{n}} \quad 1 \quad (1 \quad p_1)^n \tag{1}$$

By switching from discrete probabilities to cumulative distribution function $F(x)$, the expression (1) becomes

$$F_{\mathrm{n}}(x) \quad 1 \quad [1 \quad F_1(x)]^n \tag{2}$$

Since background radiation belongs to rare processes, the most appropriate to them is Student's distribution [14] (a symmetric distribution, very similar to a normal distribution). By applying Student's distribution into the enlargement law (2), we can not have a complete solution of the problem, since these created distribution functions of enlarged systems that do not belong to Student's distribution, although the beginning distribution does. It is shown that with a higher level of enlargement the distribution function $F_{\mathrm{n}}(x)$ converges to double-exponential distribution (*i. e.*, the distribution of extreme values, and it has for a consequence curvature of distribution functions of enlargement systems on the Student's distribution probability paper) [14-16].

By using Scrader's monogram based on the standard Student's distribution, the characteristic quantile x_{np} can be determined for the enlargement up to 10^4.

Table 1. Factors *a* and *b* for the approximation of distribution function of enlarged structures with Student's distribution with eq. (4a) and (4b)

Enlargement factor	1	10	10^2	10^3	10^4
Factor *a*	0	1.54	2.50	3.25	3.85
Factor *b*	1	0.59	0.43	0.43	0.30

Relative decrease of quantile $\Delta x_{\mathrm{p}}/\sigma_1$ in the monogram directly gives, for the beginning distribution with parameters x_1 and σ_1 and quantile $x_{1\mathrm{p}}$, the required quantile of the enlarged distribution

$$x_{\mathrm{np}} \quad x_{1\mathrm{p}} \quad \frac{\Delta x_p}{\sigma_1} \sigma_1 \tag{3}$$

However, if a distribution function of an enlarged system obtained dot by dot by using the eq. (3) is replaced by the Student's distribution, then with factors *a* and *b* (tab. 1), and parameters of the beginning distribution μ and σ, it yields

$$\mu_{\mathrm{n}} \quad \mu_1 \quad a\sigma_1 \tag{4a}$$

$$\sigma_{\mathrm{n}} \quad b\sigma_1 \tag{4b}$$

EXPERIMENT

In the experimental part of the work, real and numeric experiments were performed.

During real experiments, semiconductor MOS structures were exposed to a gamma source ^{60}Co. The change in memory chips as a result of absorbed dose was observed. The tests were performed on erasable programmable read only memory (EPROM) memory samples. Only the influence of γ radiation onto their functionality was tested. The effect of atom displacement was not treated since it was negligible compared to the effect of the creation of free electrons and electron-hole pairs, including also surface traps [17-19]. A combined uncertainty of measurement was less than 5 % [20-22].

During numeric experiments, Monte Carlo simulation method was applied to simulate the interaction between direct ionizing radiation (proton, alpha particles, and light ions) and the insulating layer of MOS structure. The trajectory of a particle passing through the material and distribution of stopped particles within a target were simulated. The programme SRIM 2008 was used. The target depth of the model was from 0 to 100 Å (1 Å = 1 10^{-10} m).

RESULTS AND DISCUSSION

Figures 1-4 show the average differential and cumulative changes in number of errors in tested samples depending on the absorbed dose.

Based on the results shown in figs. 1-4, it was observed that with the increase of a dose, there is also the

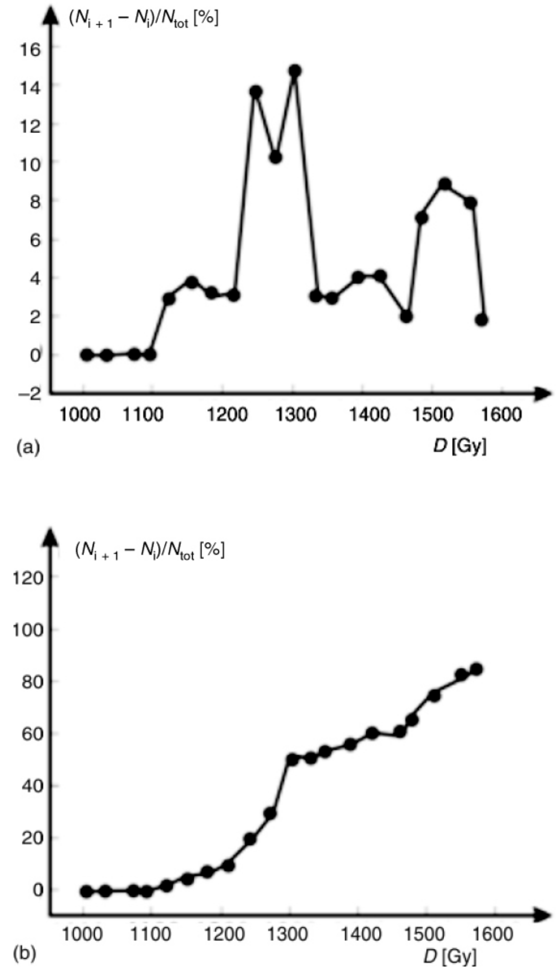

Figure 1. The average relative change in number of errors in irradiated EPROM samples (NM27C010) *vs*. the absorbed dose; (a) differential, (b) cumulative (N_{tot} = 1 048 576 bit, N_0 = 0)

increase in a number of errors in memory samples. For this reason, with the increase of the dose, there is a decrease of the functionality of EPROM components. The changes in EPROM components are reversible.

The main effect of a ^{60}Co gamma irradiation is the generation of electron-hole pairs in SiO_2 gate insulator. The number of generated electron-hole pairs depends from the absorbed dose of the gamma radiation, material characteristics and available volume. A part of electron-hole pairs is recombined. What portion of generated pairs is to be recombined depends on the power of electric field in the irradiated oxide; as the field is higher, the higher is the number of pairs to avoid recombination. The rest of the electrons are significantly more mobile than holes in SiO_2. For this reason, under the effect of the applied voltage at the gate electrons quickly leave the insulator oxide. On the other side, relatively immobile holes are trapped in the oxide or drift under the influence of the electrical field towards floating gate (FG). They contribute to the formation of a positive charge of the oxide. A part of holes which is not trapped in the oxide is integrated within FG and reduces the number of electrons in it, thus reducing the threshold voltage.

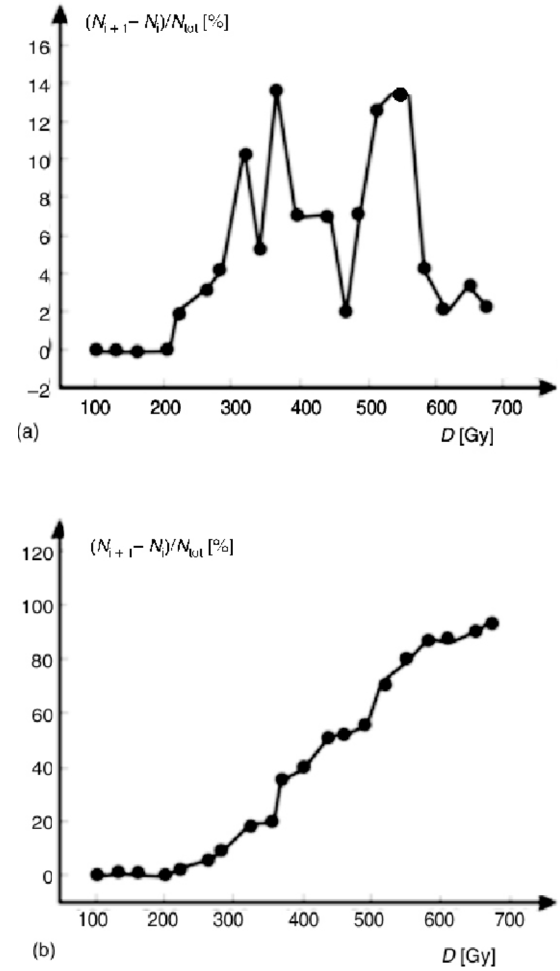

Figure 2. The average relative change in the number of errors in reprogrammed and again irradiated EPROM samples (NM27C010) *vs*. the absorbed dose; (a) differential, (b) cumulative (N_{tot} = 1 048 576 bit, N_0 = 0)

In fig. 5 the results obtained by Monte Carlo simulation of the interaction between charged particles (protons, alpha particles and lightweight ions), and the insulating layer of MOS structure are shown.

Based on the results shown in fig. 5, it can be noticed that a significant part of ionization energy is deposited in the displacement of atoms. This effect happens in big target depths, under the influence of Brag's effect [23] of the incident set.

By analyzing results shown in figs. 1-5, and with the application of the linear similarity law for interaction of electromagnetic and particle radiation [24-26], we conclude that one MOS structure, of dimensions 10 nm, which is exposed to the effects of the background radiation (gamma radiation, protons, alpha particles and lightweight ions), would have a probability of 99 % to contain a wrong data. It means that nanocomputers would be impossible for application in real conditions. Because of this, the idea of making nanocomputers with individual integrated components was abandoned, but instead, nanostructures were constructed where the components of these structures are redundant (in series and parallel). Based on such components, the information is retrieved only with a certain probability. Depending on the result ap-

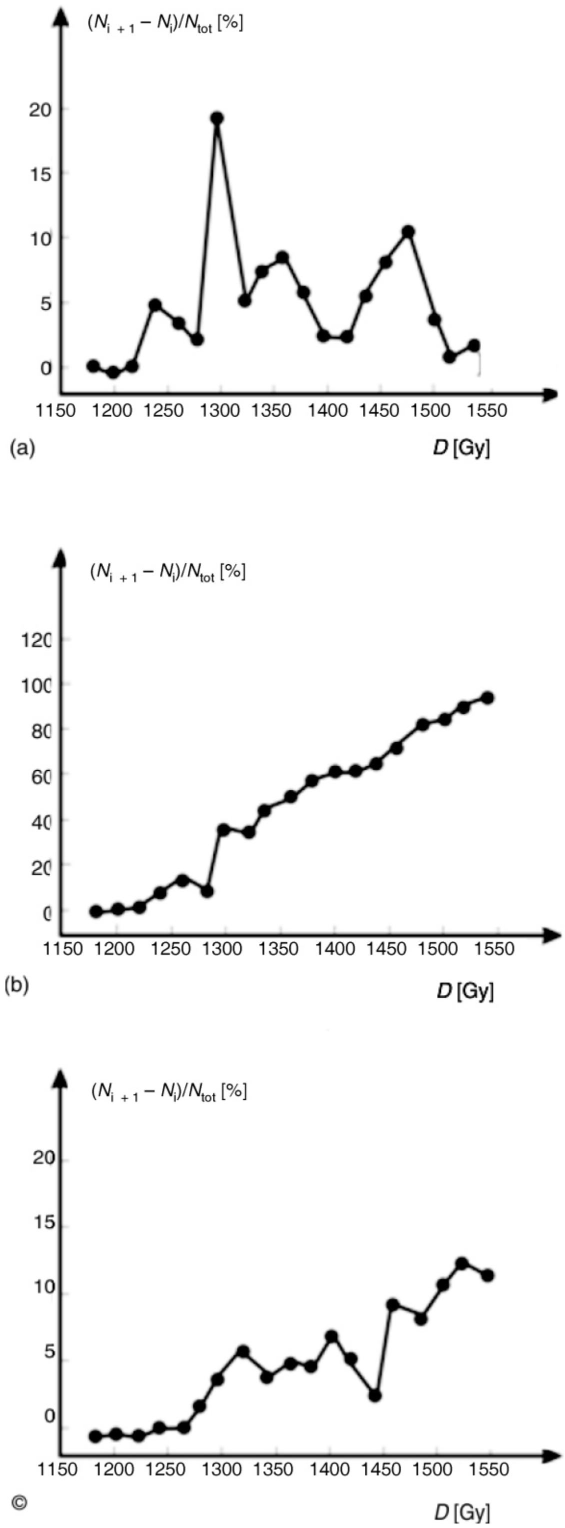

Figure 3. The average relative change in number of errors in radiated EPROM samples (NM27C512) *vs*. the absorbed dose; (a) differential, (b) cumulative (N_{tot} = 512 bit, N_0 = 0), (c) the corresponding standard deviations of results

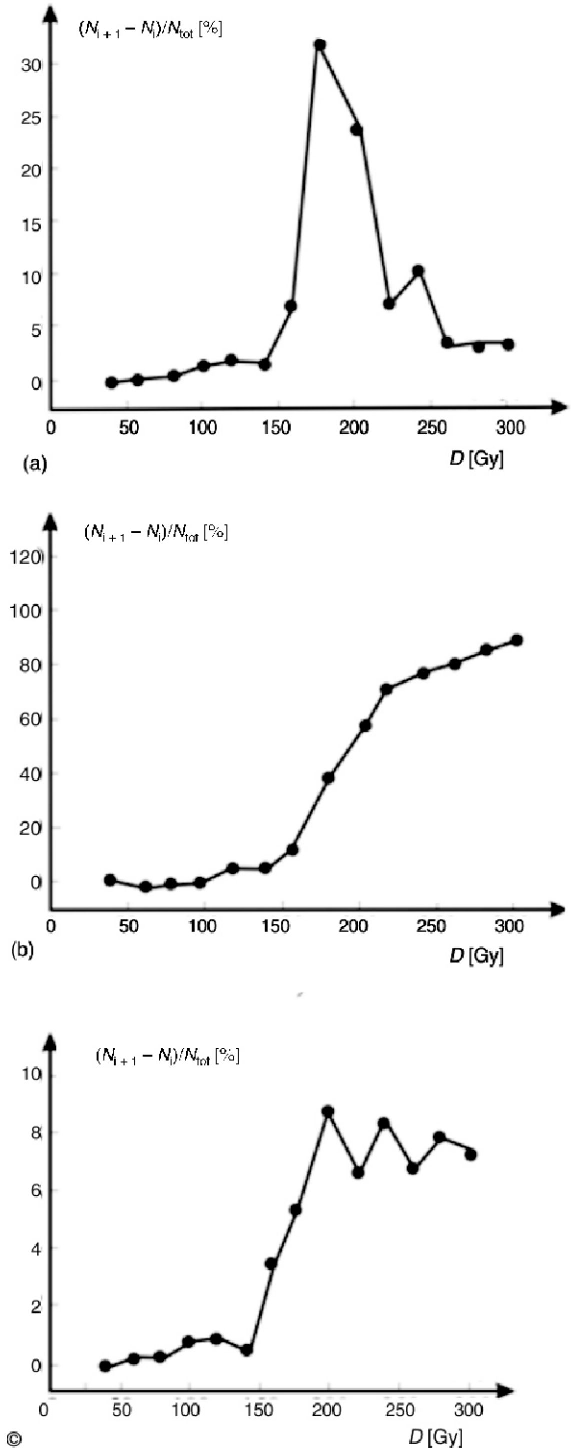

Figure 4. The average change in number of errors in reprogrammed and again irradiated EPROM samples (NM27C512) *vs*. the absorbed dose; (a) differential, (b) cumulative (N_{tot} = 512 bit, N_0 = 0), (c) the corresponding standard deviations of results

plication, the probability can be smaller or higher (depending on a redundancy level). Of course, although nanocomponents are very cheap, the number of redundant components must be minimized in order to minimize the power required for computer operation and cooling. The aim of this paper is, by applying the statistical enlargement law, to develop an algorithm that will establish a linear correlation between redundancy level of memory components and a corresponding statistical confidence of conclusion.

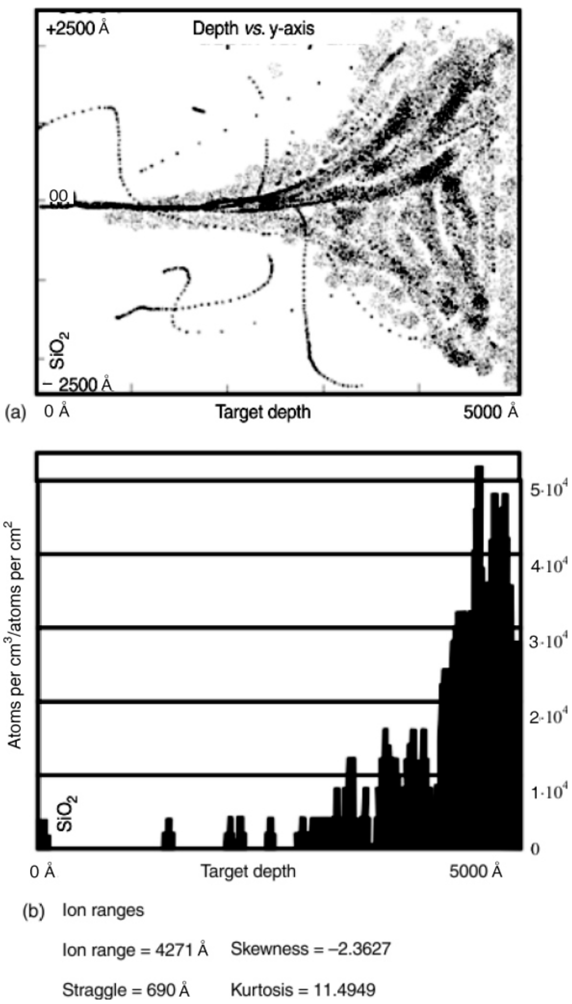

Figure 5. The simulation of 50 keV protons passing through 0.5 m thick layer of SiO_2 (500 events); (a) trajectory of photons in xOy plane, (b) distribution of stopped protons along the oxide depth

The application of the statistical enlargement law to determine a redundancy level of nanoelectronic MOS memory structures with a corresponding statistical confidence of conclusion

In the case of a parallel connection of discrete, independent MOS memories implemented in nanotechnology, the enlargement factor is one-dimensional and equal to the number of used memories. Such discrete memory allows an easier access to a computer.

In the aforementioned conditions of a small probability of damage in all memories, the following is valid [27-29]

$$p_1 \quad \frac{1}{n}; \quad p_1 \quad np_1 \tag{5}$$

$$F_n(x) \quad nF_1(x) \text{ in range } \quad \frac{1}{n} \tag{6}$$

Dot by dot estimation can be represented like in fig. 6, and from it we can gain a probability (p_n) that some of memories have wrong information in the case of n 4 parallel connected elements, for the given probability that one memory structure have a probability of p_1 to contain wrong information. The probability p_n is related to the entire structure and it characterises unreliability of information in any element, *i. e.* in more elements simultaneously.

Firstly, the application of expressions (5) and (6) allows conversion from one element to the distribution function n of parallel elements. The enlargement law, based on Student's distribution, gives a satisfying solution to the given problem. The application is also possible in the case of double-exponential distribution, and for one element F_1 (x) in the distribution function of n parallel elements, it yields

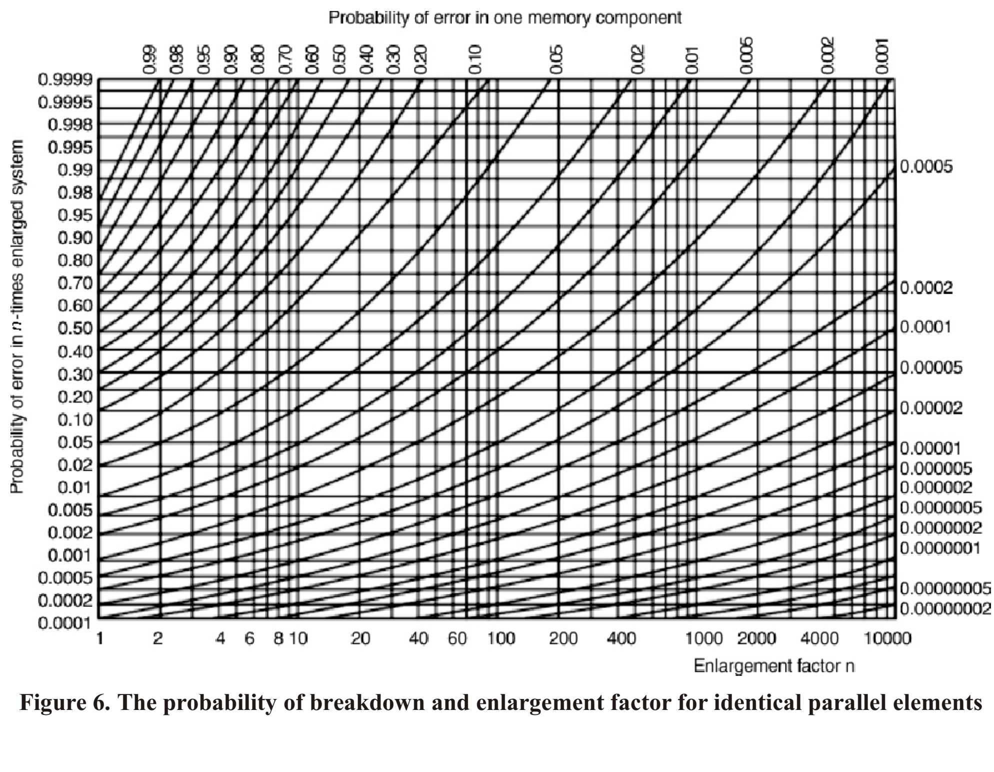

Figure 6. The probability of breakdown and enlargement factor for identical parallel elements

$$p_1 \quad 1 \quad \sqrt[n]{1 \quad p_{\rm n}} \tag{7}$$

$$F_1(x) \quad 1 \quad \sqrt[n]{1 \quad F_1(x)} \tag{8}$$

In practice, for determining a correlation between redundancy level and statistical reliability of memory recordings, the expressions (5) and (6) or (7) and (8) are equally used, (depending on the needed statistical reliability).

By reconsidering the given example, with the enlargement factor of $n = 10000$ and a probability that the individual nanotechnologically manufactured MOS memory device has a probability of wrong data caused by background radiation of 0.005, then the probability for the wrong data occurrence in the entire memory device will be $0.05 \cdot 10000^{-1}$, *i. e.* if we assume that 100 individual nanotechnology MOS devices have the same probability of having wrong content, then the information from a redundant device is 0.000005 statistically reliable. In standard conditions, this is a satisfying reliability of conclusion.

CONCLUSION

In this paper, we analyzed the issue of optimizing redundancy procedure of MOS structure for nanotechnology computers, under the influence of background radiation, with a satisfying statistical uncertainty. It is shown that in the case of identical redundant components, the statistical enlargement law gives more than satisfying results.

APPENDIX

Memories in digital systems represent components where you can store and from which you can read information. Today, it is feasible to make memory components where it is possible to store all written texts in the world. During a digital information processing, they have a task to accept and permanently store binary information, so as they can be reused after the desired time period.

From a logical viewpoint, memory is organised as a matrix cell, where, in one cell, you can store one bit of information. The cells are grouped in rows of a matrix.

Every row in a matrix memory field has its own address used to address the location when write or read operations are performed. Each row of the matrix in fig. A.1. has 16 bits.

Depending on a medium the information is stored, the most often used memory types are a semiconductor, magnetic and optical memories. Magnetic and optical memories are mostly used for storing a large number of digital information. Write and read time of these memories is relatively long due to necessary mechanical movements of a disk or tape. Magnetic and optical memories belong to the class of *non-volatile memories* since the information remains stored even when the power is turned off.

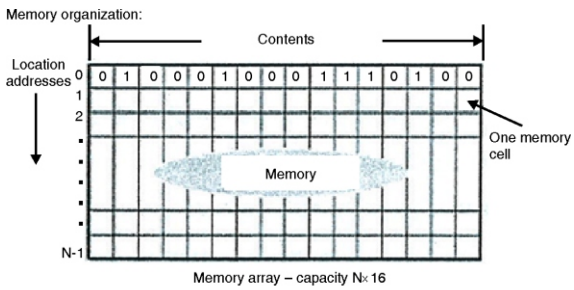

Figure A.1. Matrix memory organization

Semiconductor memories can be *static* and *dynamic*. The information in static memory remains stored until the power is on. For the information to remain stored in dynamic memory, it is necessary to refresh the content periodically (memory refresh), otherwise, the information is lost. Lately, there has been a significant development of semiconductor memories [30]. They became, due to their lower price, a huge package density, speed and organization benefits, the most significant memory medium for installation within computer systems and other digital devices.

There are two basic types of semiconductor memories. The first type is semiconductor memory where the information can be written to and read from in a random moment-random access memory (RAM). The term random access should denote that the time required for write or read operation for RAM memory is independent of the address of stored data. The information in semiconductor RAM memories is lost as soon as the power is turned off (so-called *volatile memory*), so it serves only for temporary data storage while a computer is powered. The second type is read only memory (ROM), where write and read operations are different, both physically and in terms of time. These memories are non-volatile and they serve to keep system programmes in computers, which have to be constantly available and which are not expected to change often, during computer exploitation.

Besides speed, an extremely important characteristic of each memory is the memory capacity. The memory capacity is expressed in the number of bits, or most often in the number of words, but with the note of how many bits each word contains. It is desirable for a memory to have a higher capacity. The memory capacity moves in a very wide range, depending on memory purpose.

Higher units for expressing memory capacity are: 1 byte (B) = 2^3 = 8 bits, 1 kilobyte (kB) = 2^{10} =1024 bytes, 1 megabyte (MB) = 2^{20} =1048576 bytes, 1 gigabyte (GB)= 2^{30} =1073741824 bytes. Of course, there are larger units, such as terabyte (1024 gigabytes), petabytes (1024 terabytes) and so on.

ROM memory is one with a constant content where the information is being stored using a special procedure, and when the content is stored, the memory can only be read. These are non-volatile memories for general purpose and they are used for following applications: generating binary words, number conversion, generating different functions, and so on. The most important application of ROM memories is to serve as permanent memories in computers. The data stored in ROM are always there, regardless of power. An integrated circuit of ROM memory can be taken out from computers for a longer time period and then be returned again, and the data will still be in it. For this, ROM belongs to the group of non-volatile memories. The very fact that ROM content cannot be easily changed, gives a certain level of safety against accidental changes of its content.

ROM is most often used to store system programmes we want to have available to a computer, at any time. The best example is a system ROM BIOS programme that is stored in a special ROM, in the computer motherboard. It means the programme is available when power is turned on, and the computer can use it to start the operating system. There are several types of ROM memories whose content can be changed under certain conditions. They can be called "the memory mostly used for reading" (*Read-Mostly Memory*).

Mask ROM is a memory whose content is written in a factory, during a manufacturing process and it cannot be later deleted and rewritten. They are manufactured with a similar technological procedure as microprocessors. They are used for programmes that are produced massively and they do not change often.

Figure A.2. shows the memory that represents a convertor from the binary code to Grey's code, and

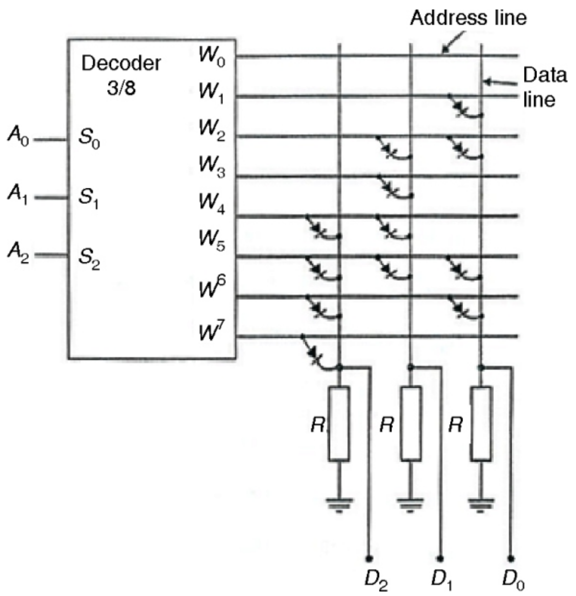

Figure A.2. The example of memory with a content written during a manufacturing process; a converter from a binary code to Grey's code

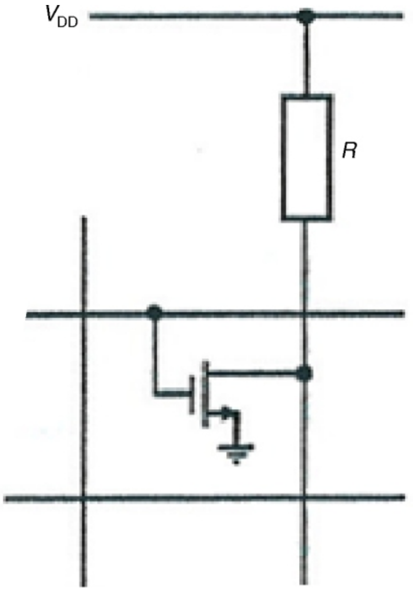

Figure A.3. The cell of ROM memory realised in NOR logic with NMOS transistors

whose matrix field is implemented in diode OR logic. When the input address signals are $A_2A_1A_0 = 000$, then the only output signal W_0 is equal to 1, and all others from W_1 to W_7 are 0. When address W_0 is not through diode physically connected to either of data lines, the output code will be $D_2D_1D_0 = 000$. If $A_2A_1A_0 = 111$, the last address line is then $W_7 = 1$, and the ROM output code is now $D_2D_1D_0 = 100$. Thus, the binary code is at the input, and at the output of ROM is Grey's code.

Instead of using diode OR logic for defining ROM content, bipolar transistors or MOSFET transistors can be used. Figure A.3 shows a cell of ROM with NMOS transistors whose matrix field cells are implemented in NOR logic. If the address line, which is connected to gate, is at logic level 1, N MOSFET channel conducts electricity, and thus, leads the data line into 0. If the address line is not 1, N channel does not conduct and the data line is on VDD, *i. e.* logic 1.

Programmable read only memory (PROM) is programmable ROM memory that can be programmed by a user itself, per its own needs. A diode PROM memory is manufactured so that diodes are placed on every cell of matrix field, in series with meltable Ni-Ch fuses, as it is presented in fig. A.4(a). When the memory is not programmed, all address lines are via fuses and diodes connected onto the data line. The user programmes the memory in a way to cause overheat-

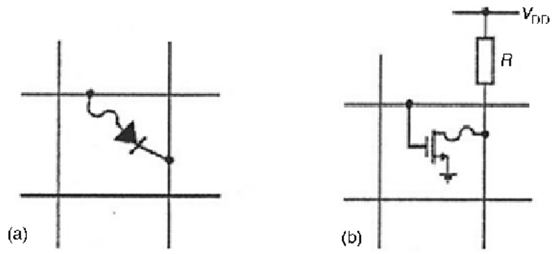

Figure A.4. The cell of PROM; (a) with a meltable Ni-Cr fuse, (b) with a drain of each transistor

ing and breaking of a fuse, in places where it wants to be logic 0. Burning is done successively in a way to address word by word and to apply a negative impulse on data line where the diode should be removed. Then, high current flows through the fuse and diode, thus burning the fuse and breaking the connection between the address line and data line.

PROM memory can be made with NMOS transistors, where fuses are connected in series with a drain of each transistor fig. A.4(b). This memory is manufactured in a way that in all places transistors are placed with fuses, which means that in all memory addresses the content is logic 0. Programming is done by burning a fuse, by applying voltage impulse on the appropriate output connector *D*, with amplitude higher than V_{DD}. Of course, addressing is done here gradually, word by word. Programming of PROM memories is performed with a special device called PROM programmer. Using a computer, desired content is written into the programmer, and then successively all locations of PROM memory are addressed, and voltage impulse is applied to burn the appropriate fuses. The main disadvantage of these memories is a fact that once written content cannot be changed.

EPROM memories use MOS transistors with the isolated gate as memory elements (fig. A.5). All transistors in the memory matrix have two gates each. The isolated gate is practically surrounded by ideal insulating material (SiO_2) and with non-isolated gate it represents a capacitive voltage divider. When the memory is not programmed, the voltage of logical 1 at the address line is sufficient to form the channel in MOS transistor via capacity divider, so the content of all locations is logic 0. Programming of the memory is performed by applying high voltage (around 25 V) on data and address line that causes a high drain current. This current creates huge acceleration of electrons which, due to their non-destructive movement, cause electrical breakdown

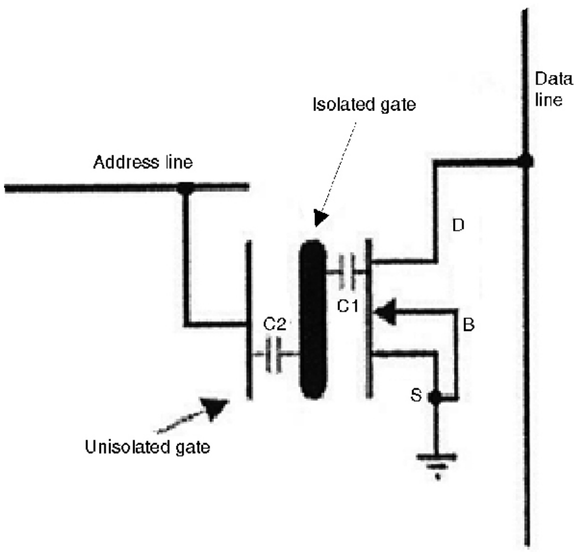

Figure A.5. The cell of EPROM that uses MOS transistor with the isolated gate as a memory element

of insulation and accumulate on isolated gate. Now, the isolated gate is at negative potential (around – 5 V), and the voltage of logical 1 (5 V) at the address line is not sufficient to form a channel in MOS transistor, and thus logical 1 is on data line. A programmed memory does not change its content more than 10 years. If such a programmed memory is exposed to the effects of ultraviolet light, in the time period of 20 minutes, the content is lost since SiO_2 becomes conductive and electrons leave the isolated gate. Each chip has a small glass window installed at the top of the package of ROM memory, and through it one can see the inner part of a memory chip. EPROM can be deleted at any time by applying light to the inner part of the chip, through this small window, in a chamber with UV light. After this, chip can be reprogrammed again. Obviously, this is more useful than a usual PROM, but it still requires a separate light for deletion.

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AUTHORS' CONTRIBUTIONS

Experiments were carried out by E. Ć. Dolićanin and I. S. Fetahović. Simulation procedure was performed by E. Ć. Dolićanin. Analysis of redundancy optimization and discussion about the results were done by both authors. The manuscript was written by E. Ć. Dolićanin. Figures were prepared by I. S. Fetahović.

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Един Ћ. ДОЛИЋАНИН, Ирфан С. ФЕТАХОВИЋ

МОНТЕ КАРЛО ОПТИМИЗАЦИЈА РЕДУНДАНЦИЈЕ НАНОТЕХНОЛОШКИХ КОМПЈУТЕРСКИХ МЕМОРИЈА У УСЛОВИМА ПОЗАДИНСКОГ ЗРАЧЕЊА

Циљ овог рада је примена статистичких законитости и закона пораста вероватноће да би се одредио степен редунданције нанотехнолошких рачунара уз унапред задату статистичку сигурност. Прво је испитана радијациона отпорност МОС меморијских компонената (комерцијалних ЕПРОМ меморија) помоћу симулације Монте Карло методом, као и експерименталном процедуром. Затим је коришћењем закона пораста вероватноће, урађена анализа оптимизације поступка редунданције МОС структура нанотехнолошки израђених рачунара, који су изложени дејству позадинског зрачења, и добијени су веома задовољавајући резултати.

Кључне речи: нанотехнолошка рачунарска меморија, оптимизација, редунданција, Монте Карло симулација, зрачење