

## THE STUDY OF RADIATION DAMAGE OF EPROM 2764 MEMORY

by

**Grzegorz DOMANSKI<sup>\*</sup>, Bogumił KONARZEWSKI, Robert KURJATA, Janusz MARZEC,  
Krzysztof ZAREMBA, Michał DZIEWIECKI, Marcin ZIEMBICKI, and Andrzej RYCHTER**

Institute of Radioelectronics and Multimedia Technology,  
Warsaw University of Technology, Warsaw, Poland

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A simple statistical theory of radiation damage of semiconductor memory has been constructed. The radiation damage of EPROM memory has been investigated. The measured number of damaged bytes is significantly lower than the expected number resulting from the purely random distribution of the damaged bits. In this way it has been proven that there is a correlation between the failures of individual memory bits which are located in the same byte.

*Key words: radiation damage, EPROM, non-volatile memory*

### INTRODUCTION

Circuits and electronic systems are exposed to ionizing radiation, especially in medicine (radiotherapy and rentgenodiagnosics), aviation, and aerospace (satellite telecommunications) [1-4]. The miniaturization of electronic components results in their increased sensitivity to ionizing radiation [5]. A physical quantity used to determine the long-term effects of ionizing radiation on the matter, is the total absorbed dose, expressed in Gy. Semiconductor devices show an increase in the degradation of their useful traits with increasing doses of ionizing radiation [6, 7]. Non-volatile semiconductor memories can be especially sensitive to ionizing radiation. The radiation affects the resistance of fundamental semiconductor materials – silicon and germanium. The resulting vacancies absorb the free charge carriers and thereby prevent them from contributing to the electric current. The ion beam can displace atoms in lattice. Damages caused by such displacement can affect the whole range of memory cell parameters. A high energy gamma-radiation can break regular bonds between the oxide atoms. It has become a standard practice in prediction of radiation effects in materials to rely on simulations of radiation transport by means of Monte Carlo method.

The EPROM is a special type non-volatile memory that is electrically programmable, and erasable by ultraviolet light. Each bit storage location of an EPROM consists of a single field-effect transistor (FET). The FET transistor consists of a channel in the semiconductor. An

insulating layer of oxide is placed over the channel, then a conductive gate electrode is deposited, and a further thick layer of oxide is deposited over the gate electrode. The floating gate electrode has no electrical connections to other parts of the transistor and is completely insulated. The control gate is placed over the floating gate. Storing data in memory requires applying a higher voltage to the transistors. This creates an avalanche discharge; the electrons have enough energy to pass through the insulating oxide layer and accumulate on the floating gate electrode. Forcing the electric charge on the gate of the memory cell gives a logical output “0” and the lack of that charge gives a logical output signal “1”. The operation of low energy X-rays and gamma rays causes mainly discharge of static charge, then change programming condition of the memory cell and replace its bit value “0” to “1”. The cumulative nature of gamma radiation effects observed in EPROM components are due to the fact that not all holes trapped at radiation induces states are annealed during the UV erasure procedure [6].

This paper presents the results related to the radiation damage of EPROM memory. The aim of the work is the examination of statistical correlations between the damaged bits within the same bytes. A simple statistical theory of radiation damage of semiconductor memory has been constructed.

### THEORY

We assume that whether the memory cell is damaged or not, it does not depend on the adjacent cells, but only on the dose accumulated in the cell and on the

<sup>\*</sup> Corresponding author; e-mail: gdomans@ire.pw.edu.pl

cell's sensitivity expressed by means of dose threshold. The cell resistance to the radiation damage depends on many factors. The cell one bit works properly if its accumulated dose is below the dose threshold. If the dose is over the threshold, the cell is damaged. The thresholds vary from cell to cell. For the whole chip containing many individual bits we can define a chip threshold dose distribution. We assume that the threshold dose distribution in the chip has a normal distribution with parameters  $\mu$  and  $\sigma$ . Integrated circuits have been exposed to radiation in steps by increasing the absorbed dose of radiation within each step in order to determine the parameters of the threshold dose distribution. Assume the definitions of symbols:

$x$  – is the radiation dose,  $y$  – the probability of bit error,  $z$  – the probability of byte error,  $\Delta x_i$  – the dose in the  $i$ -th irradiation,  $x_i$  – a cumulative dose after the  $i$ -th irradiation,  $i = 1, \dots, N$ ,  $N$  – the number of exposures,  $y_i$  – the ratio of the number of damaged bits to the number of all bits in the memory chip after  $i$ -th irradiation, and  $z_i$  – the ratio of the number of erroneous bytes to the number of all bytes in the memory chip after  $i$ -th irradiation. The total absorbed dose is the sum of all partial doses

$$x_i = \sum_{k=1}^N \Delta x_k \quad (1)$$

We assume the dependence of  $y$  on the dose  $x$

$$y(x) = \frac{1}{2} \left[ 1 + \operatorname{erf} \left( \frac{x - \mu}{\sigma \sqrt{2}} \right) \right] \quad (2)$$

where  $\operatorname{erf}(x)$  – error function, defined as [8]

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt \quad (3)$$

The derivative of the error function is a Gaussian distribution function. The first derivative of the cumulative variable  $y$  is calculated in order to fit the theoretical curve to the measurement data

$$y_j = y(x_j), \quad j = 1, 2, \dots, N \quad (4)$$

Then estimates of the parameters are determined

$$\hat{\mu} = \frac{\sum_{j=1}^N x_j y_j}{\sum_{j=1}^N y_j} \quad (5)$$

$$\hat{\sigma} = \frac{\sum_{j=1}^N (x_j - \hat{\mu})^2 y_j}{\sum_{j=1}^N y_j} \quad (6)$$

The standard deviation of the parameter  $\hat{\mu}$  is calculated

$$\sigma(\hat{\mu}) = \frac{\sqrt{\sum_{j=1}^N \sigma^2 x_j y_j}}{\sum_{j=1}^N y_j} \quad (7)$$

Assuming that the variance of the dose in the  $k$ -th irradiation is fixed and equals  $\sigma^2(\Delta x)$ , we can write

$$\sigma^2 \sum_{j=1}^N y_j \sum_{k=1}^j \Delta x_k = \sigma^2(\Delta x) \sum_{j=1}^N j (y_j)^2 \quad (8)$$

Thus, the standard deviation of the parameter is given by the formula

$$\sigma(\mu) = \frac{\sigma(\Delta x) \sqrt{\sum_{j=1}^N j (y_j)^2}}{\sum_{j=1}^N y_j} \quad (9)$$

The standard deviation of the parameter is calculated

$$\sigma(\hat{\sigma}) = \sqrt{\sum_{j=1}^N \left( \frac{\partial \hat{\sigma}}{\partial \Delta x_j} \right)^2 \sigma^2(\Delta x_j)} = (\Delta x) \sqrt{\sum_{j=1}^N \left( \frac{\partial \hat{\sigma}}{\partial \Delta x_j} \right)^2} \quad (10)$$

The above partial derivatives have been calculated numerically.

Knowing the probability of bit damage  $p$  for a given dose, one can calculate the theoretical probability of byte damage

$$P_{\text{byte}} = 1 - P_0 \quad (11)$$

where  $P_0$  is the probability that none of the bits in the byte is damaged. The probability  $P_0$  can be calculated [8]

$$P_0 = \sum_{k=0}^n p^k (1-p)^{n-k} \quad (11)$$

where  $n = 8$  and  $k = 0$

Therefore

$$P_{\text{byte}} = 1 - (1-p)^8 \quad (12)$$

The difference between the byte failure probability calculated from the bit failure probability and the measured one may be due to the correlations between the failures of bits within the same byte. Let absolute difference between the measured and the theoretical number of damaged bytes be  $\Delta N_{\text{byte}}$ . The variance of the theoretical number of damaged bytes is

$$\operatorname{var}(N_{\text{byte}}) = N_{\text{byte}} \left[ 1 - \frac{N_{\text{byte}}}{N_0} \right] \quad (13)$$

where  $N$  is the total number of bytes in the chip.

The standard deviation of the theoretical number of damaged bytes is

$$\sigma(N_{\text{byte}}) = \sqrt{\operatorname{var}(N_{\text{byte}})} = \sqrt{N_{\text{byte}} \left[ 1 - \frac{N_{\text{byte}}}{N_0} \right]} \quad (14)$$

The difference between the measured and the theoretical number of damaged bytes is statistically significant if it is more than three times larger than the standard deviation

$$\Delta N_{\text{byte}} \geq 3\sigma(N_{\text{byte}}) \quad (15)$$

The inequality is true for the quantile  $q = 0.99$  and the degree of freedom greater than or equal to 7.

More accurately, one sample  $t$ -test has been used

$$t = \frac{\Delta N_{\text{byte}}}{\sigma(N_{\text{byte}})} \quad (16)$$

The hypotheses that two mean values of damaged bytes (measured and theoretical) are equal is rejected, if

$$|t| > t_{m,q} \quad (17)$$

where  $t_{m,q}$  is the quantile of  $t$ -distribution and  $m$  – a degree of freedom,

$$m = N_{\text{byte}} - 1 \quad (18)$$

The parameter  $q$  is calculated for two-sided test from the formula

$$q = 1 - \frac{\alpha}{2} \quad (19)$$

where  $\alpha$  is the a level of significance.

### THE EXPERIMENT

Three EPROM chips type 2764 have been used to investigate the radiation damage caused by X-rays. Two chips have been manufactured by ST Microelectronics (hereinafter designated Chip no. 1 and Chip no. 2), and one by SGS Ates (hereinafter referred to Chip no. 3). The X-ray tube L8121-03 manufactured by the company Hamamatsu has been used as the X-ray source. The tube operating voltage has been 100 kV and the current has been 350  $\mu$ A. Under these conditions at the distance of 1 m from the focus, the dose rate measured in the air by dosimeter VAJ-15 has been approx. 550 R/h. The tested memory chips have been exposed to radiation at a distance of 7 cm – so that the dose rate has been achieved at level 115 kR/h (32 R/s). Such a high dose rate has allowed us to use relatively short exposure times. Even for an air dose level 10000R (100 Gy) the sufficient exposition time has been approx. 5 minutes.

The dose  $x$  has been obtained from the following equation

$$x = x_{r_0} t_e \frac{r_0^2}{r} \quad (20)$$

where  $x$  is the dose,  $r_0$  – the distance from X-ray source to the dose rate meter,  $r$  – the distance from X-ray source to the tested chip,  $x_{r_0}$  – the measured dose rate at the distance  $r_0$ , and  $t_e$  – exposition time.

The following sources of Type B uncertainty in the dose measurement can be identified:

- uncertainty of dose rate at the distance  $u(x_{r_0})$ ,
- uncertainty of exposition time  $u(t_e)$ ,
- uncertainty of the distance from the X-ray source to the test chip  $u(r)$ , and
- uncertainty of the distance from the X-ray source to the dose rate meter  $u(r_0)$ .

The combined uncertainty is computed from the following equation

$$u^2(x) = \left(\frac{\partial x}{\partial x_{r_0}}\right)^2 u^2(x_{r_0}) + \left(\frac{\partial x}{\partial t_e}\right)^2 u^2(t_e) + \left(\frac{\partial x}{\partial r_0}\right)^2 u^2(r_0) + \left(\frac{\partial x}{\partial r}\right)^2 u^2(r) \quad (21)$$

The values of the above partial derivates are

$$\frac{\partial x}{\partial x_{r_0}} = t_e \frac{r_0^2}{r} \frac{x}{x_{r_0}} \quad (22)$$

$$\frac{\partial x}{\partial t_e} = x_{r_0} \frac{r_0^2}{r} \frac{x}{t_e} \quad (23)$$

$$\frac{\partial x}{\partial r_0} = 2x_{r_0} t_e \frac{r_0}{r^2} \frac{x}{r_0} \quad (24)$$

$$\frac{\partial x}{\partial r} = 2x_{r_0} t_e \frac{r_0^2}{r^3} \frac{x}{r} \quad (25)$$

The uncertainty of dose rate is estimated from the manufacturer's data as  $u(x_{r_0}) = 0.0866 x_{r_0}$ ; the uncertainty of exposition time is assumed to be proportional to the time  $u(t_e) = 0.003 t_e$ ; the uncertainty of distances  $r$  and  $r_0$  are constants  $u(r_0) = 0.5$ ,  $u(r) = 0.5$ .

The combined dose uncertainty is equal

$$u^2(x) = x^2 \left[ \frac{u^2(x_{r_0})}{x_{r_0}^2} + \frac{u^2(t_e)}{t_e^2} + \frac{4u^2(r_0)}{r_0^2} + \frac{4u^2(r)}{r^2} \right] \quad (26)$$

Let us introduce the relative standard uncertainty

$$\delta(x) = \frac{u(x)}{x} \quad (27)$$

$$\delta(x_{r_0}) = \frac{u(x_{r_0})}{x_{r_0}} \quad (28)$$

$$\delta(t_e) = \frac{u(t_e)}{t_e} \quad (29)$$

$$\delta(r_0) = \frac{u(r_0)}{r_0} \quad (30)$$

$$\delta(r) = \frac{u(r)}{r} \quad (31)$$

Then

$$\delta^2(x) = \delta^2(x_{r_0}) + \delta^2(t_e) + 4\delta^2(r_0) + 4\delta^2(r) \quad (32)$$

This equation can be written

$$\delta^2(x) = \sum_{i=1}^4 (c_i \delta_i)^2 \quad (33)$$

where

$\delta_1 = \delta(x_{r_0})$ ,  $\delta_2 = \delta(t_e)$ ,  $\delta_3 = \delta(r_0)$ ,  $\delta_4 = \delta(r)$ , and  $c_i$  – sensitivity coefficient.

The calculations of measurement instrument uncertainty are summarized in tab. 1. The coverage factor  $k_p$  used to calculate the expanded uncertainty has been taken from [9].

One can obtain

$$\delta(x) = \frac{u(x)}{x} = 0.1197 \quad (34)$$

For example, for the dose of 1000 Gy, the standard uncertainty is  $u(x) = x\delta(x) = 119.7$  Gy.

**Table 1. Uncertainty budget of measurement instrument uncertainty for dose measurement**

Input quantity	$X_i$	The range of variation of the variable	Probability distribution function	Relative standard uncertainty $\delta_i$	Sensitivity coefficient $c_i$	Contribution to the relative standard uncertainty $ c_i\delta_i $
Dose rate at $r_0$	$x_{r_0}$	$\pm 0.15^* x_{r_0}$ Gy/s	Rectangular $k_p = 1.732$	0.0866	1	0.0866
Exposition time	$t_e$	$\pm 0.003^* t_e$ s	Rectangular $k_p = 1.732$	0.0017	1	0.0017
Distance from source to dosimeter	$r_0$	$\pm 0.5$ cm	Rectangular $k_p = 1.732$	0.0029	2	0.0058
Distance from source to chip	$r$	0.5 cm	Rectangular $k_p = 1.732$	0.0412	2	0.0825

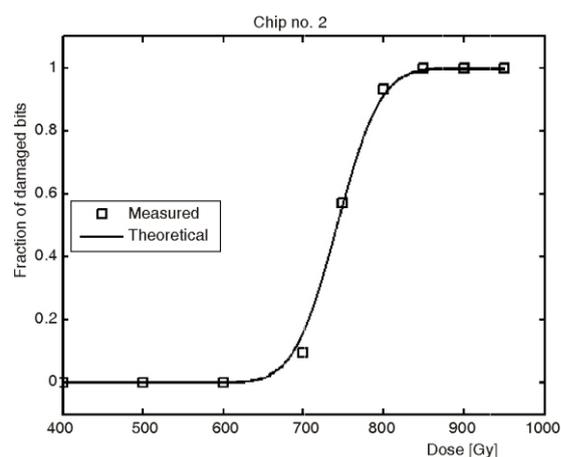
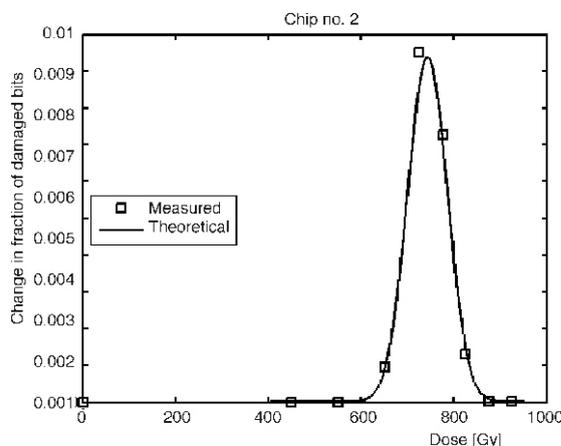
## RESULTS AND DISCUSSION

For preliminary estimate of the range of doses required to erase a memory, the Chip no. 1 has been used, which has been irradiated with such targeted exposure times, that the accumulated dose has been 100 Gy, 300 Gy, and 1000 Gy. The correctness of the information previously recorded in the memory has been tested after obtaining each of the doses. For dose of 100 Gy and 300 Gy the content of the memory has not been damaged (no errors). For dose of 1.000 Gy the memory has been erased – contained only “1” states. Unfortunately the chip used in the experiment can not be programmed again (even after resetting procedure using the UV).

To accurately determine the threshold for damage of EPROM memory, the Chip no. 2 has been irradiated with such targeted exposure times that the accumulated dose has been in the range of 400-950 Gy. The dose initially has been increased in increments of 100 Gy, followed by the increments of 50 Gy. As before the content of the EPROM has been a recurring 16-character string (ASCII text: LABORATORIUM TMIK). A simple C program (BIN\_COMPARE) has been used to assess the degree of damage. It has compared the original content memory storage and the content after exposure and has calculated the number of different bytes and bits. The results of the test of Chip no. 2 have been summarized in tab. 2. The results are shown graphically in figs. 1 and 2. The fraction of damaged bits as a function of dose is shown in fig. 1. The change in fraction of damaged bits as a function of dose for the Chip no. 2 is shown in fig. 2. These fraction distributions can be used as the probability distribution estimations.

**Table 2. The radiation damage of the Chip no. 2**

Dose [Gy]	Number of damaged bytes	Number of damaged bits	Value of $t$ statistics
400	0	0	–
500	0	0	–
600	0	0	–
700	2604	3764	44.54
750	7051	22788	36.11
800	8078	37282	10.75
850	8191	39877	1.00
900	8192	39935	0
950	8192	39936	0

**Figure 1. The fraction of damaged bits as a function of dose for the Chip no. 2****Figure 2. The change in fraction of damaged bits as a function of dose for the Chip no. 2**

For the dose of 950 Gy, the memory has been erased. It has contained the “1” only. However, as before, the integrated circuit cannot be programmed again (even after the reset procedure using the UV). The results allow one to specify the mean value of the dose needed to damage memory cells to be about 750 Gy. The measured distribution of the fraction of damaged bits has been fitted to the theoretical distribution given by (2). The obtained parameters are as follows:  $\hat{\mu}$  743 16Gy and  $\hat{\sigma}$  42 2Gy

The change in fraction of damaged bits as a function of dose for the Chip no. 2 is shown on fig. 2.

The similar procedure has been applied to the fraction of damaged bits. It has been fitted to the theoretical

distribution. The expected value for the distribution has been obtained as follows:  $\hat{\mu}_{\text{byte}} = 709$  and  $\hat{\sigma}_{\text{byte}} = 56$  Gy

The difference between the expected values for bit and byte distributions for Chip no. 2 is statistically significant. For example, for the dose 700 Gy

$$\frac{\Delta N_{\text{byte}}}{\sigma(N_{\text{byte}})} = 44.5$$

The theoretical and measured dependencies of the fraction of damaged bytes for the Chip no. 2 are shown in fig. 3. The theoretical fraction of damaged bytes has been calculated in two ways: from the measured distribution of defective bits (solid line) and from the measured distribution of defective byte (dashed line). A notable reduction in the actual number of bad bytes in relation to the number of ones expected on the number of corrupted bits is visible.

The next integrated circuit Chip no. 3 has been tested. The memory has been filled with zeros. It adopted the contents of the EPROM to improve the objective evaluation of the degree of damage. In the case of the memory filled with ASCII text one can observe the progressing damage of its content but due to the fact that certain bits have value "1" from the beginning, their damage is not visible easily. The integrated circuit Chip no. 3 has been irradiated with exposure times selected so that the accumulated dose ranges between 400-1100 Gy in steps of 50 Gy. To assess the degree of damage, the aforementioned program BIN\_COMPARE has been used. The obtained results of Chip no. 3 test are shown in tab. 3.

For the dose of 1100 Gy the memory has been erased. It contained the same values ones. Otherwise than for previous systems, in the case of Chip no. 3, there has been no permanent damage of the memory. The Chip no. 3 allows further programming. It also notes a significantly higher threshold for damage – it can be determined about 700 Gy.

The obtained parameters are:  
 $\hat{\mu} = 901 \pm 30$  Gy and  $\hat{\sigma} = 42 \pm 2$  Gy

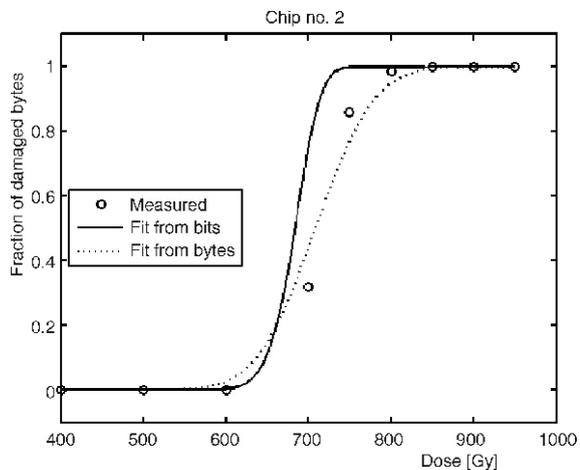


Figure 3. The theoretical and measured dependencies of the fraction of damaged bytes for the Chip no. 2

Table 3. The radiation damage of the Chip no. 3

Dose [Gy]	Number of damaged bytes	Number of damaged bits	Value of <i>t</i> statistics
400	0	0	–
450	0	0	–
500	0	0	–
550	0	0	–
600	0	0	–
650	0	0	–
700	0	0	–
750	2	2	0.00
800	379	413	1.32
850	3433	6457	26.56
900	7189	31970	32.50
950	8157	58142	5.93
1000	8192	65148	0
1050	8192	65532	0
1100	8192	65536	0

The fraction of damaged bits as a function of dose for the Chip no. 3 is shown in fig. 4. The change in fraction of damaged bits as a function of dose for the Chip no. 3 is shown in fig. 5.

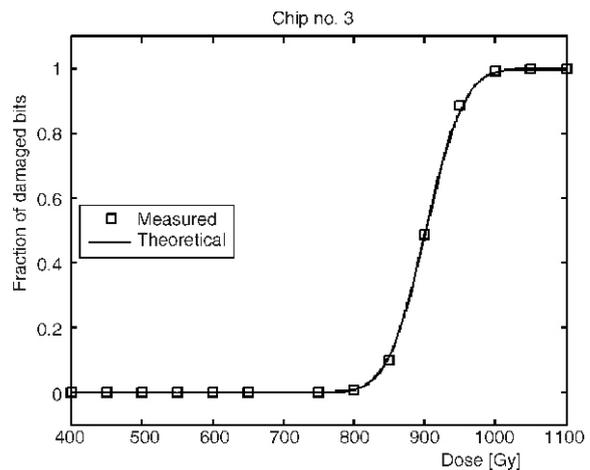


Figure 4. The fraction of damaged bits as a function of dose for the Chip no. 3

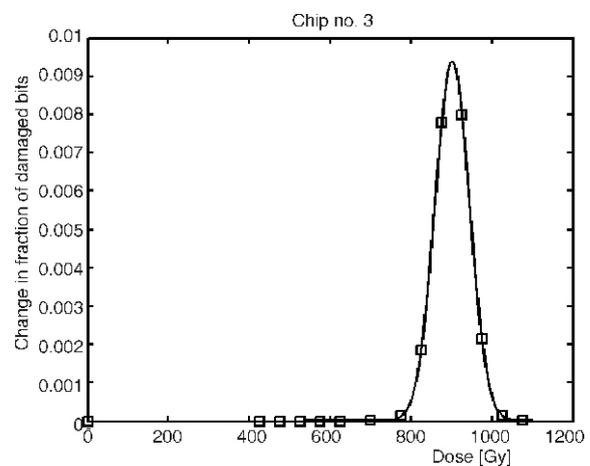
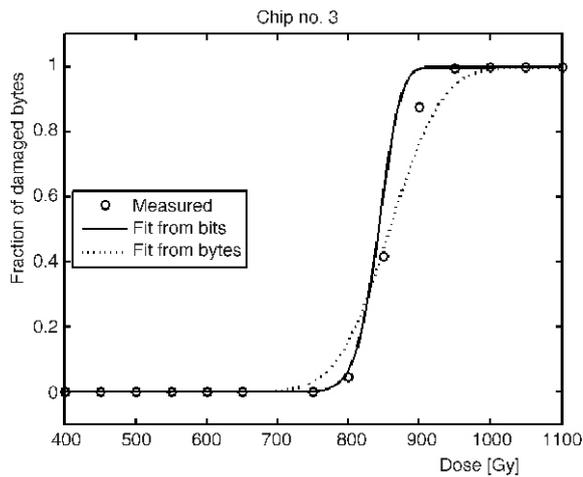


Figure 5. The change in fraction of damaged bits as a function of dose for the Chip no. 3



**Figure 6.** The theoretical and measured dependencies of the fraction of damaged bytes for the Chip no. 3

Also, the fraction of damaged bytes has been fitted to the theoretical distribution. The expected value and the standard deviation are  $\hat{\mu}_{\text{byte}} = 858$  and  $\hat{\sigma}_{\text{byte}} = 58$  Gy.

The difference between the expected values for bit and byte distributions for the Chip no. 3 is statistically significant. For example, for the dose of 850 Gy

$$\frac{\Delta N_{\text{byte}}}{\sigma(N_{\text{byte}})} = 26.5$$

The theoretical and measured dependencies of the fraction of damaged bytes for the Chip no. 3 are shown in fig. 6. The theoretical fraction of damaged bytes has been calculated in two ways: from the measured distribution of defective bits (solid line) and from the measured distribution of defective byte (dashed line). As in the case of the Chip no. 3, a notable reduction in the actual number of bad bytes in relation to the number of ones expected on the number of corrupted bits is visible.

It is evident that the statistical analysis plays an important role in radiation physics experiments [10].

## CONCLUSIONS

The study has helped to determine the radiation resistance of memory chips type 2764. The simple statistical theory of radiation damage of semiconductor memory has been constructed. The experimental results have matched the assumed theoretical curve. The values of the parameters as well as the uncertainty of these parameters have been estimated. The number of damaged bytes is significantly lower than the number resulting from purely random distribution of the damaged bits. In this way, the correlation between the failures of individual memory bits located in the same byte has been shown. The results can serve as the guidelines for the design of electronic circuits exposed

to the prolonged high levels of ionizing radiation. Another application of the obtained results may be an appropriate use of redundant coding data in the semiconductor memories, exposed to radiation. Encoding data should take into account the increased likelihood of errors on adjacent bits.

## AUTHORS' CONTRIBUTIONS

Theoretical analysis was carried out by G. Domanski, and B. Konarzewski. The experiments were carried out by B. Konarzewski, J. Marzec, and M. Dziewiecki. The manuscript was written by G. Domanski, R. Kurjata, K. Zaremba, and M. Ziembicki. The figures were prepared by A. Rychter. All authors analysed and discussed the results.

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**Гжегож ДОМАНСКИ, Богумил КОНАЖЕВСКИ, Роберт КУРЈАТА, Јануш МАЖЕЦ,  
Кшиштоф ЗАРЕМБА, Михал ЂЈЕВЈЕЦКИ, Марћин ЗЈЕМБИЦКИ, Анђеј РИХТЕР**

### **ИСПИТИВАЊЕ РАДИЈАЦИОНОГ ОШТЕЋЕЊА ЕПРОМ 2764 МЕМОРИЈЕ**

У овом раду приказана је једноставна статистичка теорија радијационог оштећења полупроводничких меморија и извршено је испитивање радијационог оштећења ЕПРОМ меморије. Измерени број оштећених бајтова значајно је нижи од очекиваног броја што је последица потпуно насумичне расподеле оштећених битова. На овај начин доказано је да постоји корелација између отказивања појединачних битова меморије који се налазе у оквиру истог бајта.

*Кључне речи: радијационо оштећење, ЕПРОМ, трајна меморија*

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