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Comparative Radiation Hardness Experimental Analysis, According to "Logical Zero" (U_{OL}) Parameter, of Bipolar Logic IC, Manufactured with Different Preliminary Radiation and Thermal Treatment

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Abstract: Results of experimental comparison of the logic bipolar IC radiation hardness, under the action of electrons with energy ≈ 5.5 MeV, dose $1.25 \cdot 10^{13}$ cm^{-2}, γ-quants from ^{60}Co source. The inequality of Chebyshev, differential, and probability entropy were used. ICs were manufactured by the standard technology and with the use of different preliminary radiation and thermal treatments (irradiation by α-particles and accelerated electrons, followed by isothermal annealing after the technological irradiation). The possibility of sufficiently increasing (up to 40 times) the radiation resistance of logic ICs according to the U_{OL} criterion ("logical zero" voltage level) by using irradiation with α-particles of a radioisotope source ($\Phi\alpha = 8 \cdot 10^{10}$ cm-2, isothermal annealing at 350 °C for 20 minutes) has been experimentally demonstrated. The application of pre-radiation and thermal treatment, using 5.5 MeV electron technological irradiation ($\Phi_{electrons} = 2 \cdot 10^{16}$ cm^{-2}, isothermal annealing at 350 °C for 15 minutes), does not lead to a significant change in ICs radiation resistance (improvement ≈15 %). The use of the test γ-irradiation shows the complex nature of dependencies (presence of extremes with different probabilities) requires the use of entropy analysis to determine the efficiency of the application of different preliminary radiation-thermal treatment of IC (technological irradiation with α-particles or accelerated electrons). This method of analysis shows that technology, based on preliminary electron irradiation, may be a reason for high IC sample failure. For the continuous distributions of U_{OL}, the differential entropy is proposed to be calculated by the newly derived formula, which uses the expressions for the probability of IC U_{OL}. The increase in standard technology IC distribution complexity of "logic zero level", which is expressed by the bimodal distribution of U_{OL} before test irradiation, leads to a significant increase in probability entropy after γ-irradiation and thus reduces the numerical value of IC sample probability failure. This effect requires further analysis, for example, to determine whether it is present in IC samples, manufactured with preliminary radiation-thermal treatment and having a bimodal distribution of U_{OL} before test irradiation.

Keywords: Experimental comparison of the radiation resistance of IC, Different preliminary radiation and thermal treatments, Irradiation by α-particles and accelerated electrons, Isothermal annealing after the technological irradiation, entropy analysis.

1. Introduction

Radiation processing is the intentional exposure of products and materials to ionizing radiation to achieve a desired change in their physical and chemical properties. The application of radiation technology in industrial production is a complex scientific and technical problem, which is because to design the application of radiation technology and the corresponding equipment for it, it is necessary to analyze the main effects that determine the reaction of the object (structure) to which the technological irradiation is applied [1, 2]. Applications of radiation process technologies increase industrial manufacturing efficiency, environmental protection, and add value to products. Radiation processing technologies are used during the manufacturing of many products, such as wire and cable, automobile tires, plastic films, and surface treatment of materials [3].

1.1. Use of Radiation Technologies in Semiconductor Production

Radiation technology is widely used in IC and discrete devices technology [4]. The physical basis of such technologies is studied in detail [5]. In the manufacture of high-frequency bipolar transistors, to reduce the charge accumulated in the base and collector regions, it is necessary to ensure low lifetimes of minority charge carriers [6]. This is achieved by introducing recombination centers, impurities, and radiation defects into the crystal. Au is often used as an impurity center of recombination, which can be located both in the nodes and in the internodes of the lattice, but the gold dissolved in silicon can change from one state to another, settle on lattice defects, as well as by various sinks, for example, passivation IC layers. The radiation processing technique, as compared to the introduction of metal impurities in semiconductors, suggests precision, reliability, and reproducibility of the technological process. Precise control of the concentration of defects generated provides more uniform electrical properties for the device, thereby improving its quality. Radiation technology solves common diffusion problems, for example, the non-uniform depth distribution of impurities. The stability of radiation-induced defects is assured for over 40 years at operational temperatures ≤ 125 °C. The calculations and analyses reported in [7] demonstrated that radiation and thermal treatments of certain types of bipolar silicon ICs at the final stage of crystal production (before cutting and packaging operations) are suitable for reducing their sensitivity to single radiation events. Preliminary experimental studies were proposed to be carried out on packaged products.

1.2. Recent Practical Results on Radiation Hardness Improvement by Preliminary Radiation and Thermal Treatment

In [8], the possibility of sufficiently increasing the radiation resistance of logic ICs according to the U_{OL} criterion by using preliminary radiation and thermal treatment, including irradiation with α-particles of a radioisotope source with $\Phi_\alpha = 8 \cdot 10^{10}$ cm^{-2} and isothermal annealing at 350 °C for 20 minutes, has been experimentally demonstrated. Comparison of the radiation resistance of ICs, manufactured following standard technology and using preliminary radiation and thermal treatment, was carried out by the inequality of Chebyshev, expressed in a standard form [9] as follows, formula (1):

$$P(|X - m_X| \geq \varepsilon) \leq \frac{D_X}{\varepsilon^2} \tag{1}$$

The probability that the deviation of the random variable X from its mathematical expectation m_X by absolute magnitude is not less than any positive number of U_{OL}, ε, and is bounded (limited) at the top by the value $\frac{D_X}{\varepsilon^2}$, where D_X is the variance of the random variable X. Actually, it is the probability of U_{OL} reaching the maximum allowed ε value.

The results showed that, with sufficient accuracy for practical application, it could be assumed that the use of α-technology reduces the probability of failure of the logical IC under the action of ionizing radiation, according to the U_{OL} criterion, by approximately 40 times when irradiated with accelerated electrons. It may even be correct to say that the increase in radiation resistance is not specific to the IC sample, but rather to the investigated ***technology***. Results of the experiment, carried out in [8], are briefly exposed in Table 1.

Table 1. Definition of the U_{OL} distribution parameters of a logic IC manufactured using Standard technology and technology based on technological α-irradiation before and after electron irradiation with an energy of ≈ 5.5 MeV

No	Technology Type	Weighted average of U_{OL}, $m(U_{OL})$, V	Dispersion, D, V^2	Standard deviation, $\sqrt{D}$, V
Before irradiation with relativistic electrons				
1.	Standard	0.318	$4.082 \cdot 10^{-5}$	$6.389 \cdot 10^{-3}$
2.	Use of technological α-irradiation	0.320	$3.225 \cdot 10^{-5}$	$5.679 \cdot 10^{-3}$
After irradiation with relativistic electrons ***(≈ 5.5 MeV with a dose ≈ of 1.25·10^{13}cm^{-2})***				
3.	Standard	0.330	$7.053 \cdot 10^{-5}$	$8.398 \cdot 10^{-3}$
4.	Use of technological α-irradiation	0.324	$1.587 \cdot 10^{-6}$	$1.26 \cdot 10^{-3}$

Relative increase of U_{OL} distribution parameters (m, weighted average, for example):

$$\frac{m(U_{OL\_after\_irrad})-m(U_{OL\_before\_irrad})}{m(U_{OL\_before\_irrad})},$$

for irradiation of electrons with an energy of several MeV for standard technology (IC manufactured using Au diffusion) ≈ 3.773 %, the same for ICs manufactured by application of technological irradiation of α-particles of radioisotope source (α-technology) ≈ 1.25 % %. Therefore, the relative increase in the level of "logic zero" during irradiation of ICs manufactured using preliminary radiation and thermal treatment is approximately three times less than for devices manufactured using Au diffusion, i.e., their radiation resistance is three times *higher.*

Standard Deviation, $\sqrt{D}$, of U_{OL} for α-technology after irradiation is ≈ less than 7 times in comparison with the standard IC technology. It means a shorter "tail" of U_{OL} distribution and higher radiation hardness.

It's a very rough estimation, that's why, in our opinion, it's better to use the inequality of Chebyshev with a clear physical sense of $\frac{D_X}{\varepsilon^2}$. So, the less the Dispersion of the "logical zero" level, the higher the radiation hardness of the IC sample. It is very obvious in Fig. 1.

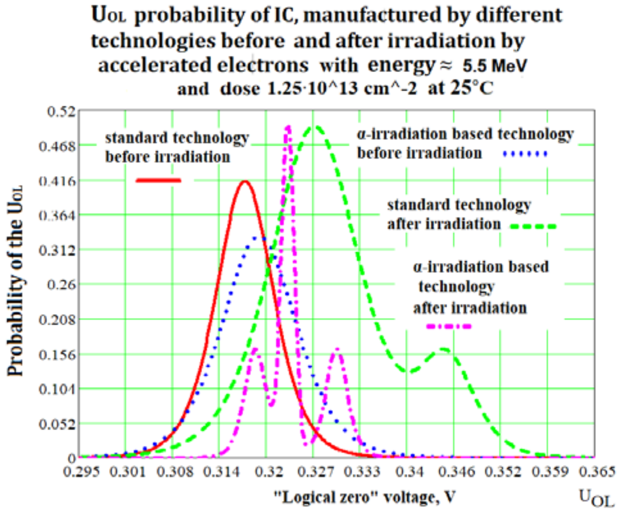


Fig. 1. Comparison of U_{OL} radiation degradation for ICs manufactured using standard technology and preliminary radiation and thermal treatment.

The following hypothesis was used to explain the obtained results from a qualitative point of view. During the test irradiation with relativistic electrons in the active thin (0.25...0.35 µm) base layers of npn IC transistors, in which prior radiation-thermal processing of wafers with IC is applied, an active self-organization occurs [10] of technological radiation defects and/or their clusters [11]. This probably leads to the formation of a quasi-periodic dependence of the probability of U_{OL} on its numerical value after radiation testing. This assumption does not contradict previously obtained results. Experimentally detected phenomena in the semiconductors related to self-organization defects when irradiation crystals with high-energy particles [12]. In silicon, irradiated with alpha particles, a periodic defect structure was observed. With a large energy dissipation in the thin layer of the crystal during irradiation, conditions can be created for self-organization of radiation defects, the consequence of which may be the formation in the defective subsystem of the crystal «supergrids» in the form of "defect walls".

Therefore, the formation of the experimentally observed quasi-periodic dependence of the U_{OL} probability during the test exposure of ICs by relativistic electrons (Fig. 1) and, as a result, the significant *decrease* in U_{OL} dispersion. It reflects "compressing" of the probability as a function of U_{OL} and was presumably associated with the self-organization of radiation defects (clusters), generated by α-particles (V-clusters), described in the relevant literature [10-12].

There is a question about the supposed active self-organization of technological radiation defects. Is it a specific feature of the application, precisely α-irradiation? Will this effect be observed when applying another technological irradiation, for example, accelerated electrons with an energy of 5...6 MeV? How will the change in the type of technological irradiation affect the radiation resistance of IC when applying other types of experiment (test) irradiation, such as γ-irradiation?

2. The Goal of the Experiment

The task of the present investigation was an *experimental* comparison of the logic bipolar IC radiation hardness, manufactured by different preliminary radiation and thermal treatments.

The feature of the work is a detailed description of the statistical processing of the obtained experimental data, which are presented in the form of histograms, as well as the calculation formulas used.

3. Experimental Methodology

3.1. Details of the Experiment

For bipolar logic circuits of the TTL-type with positive logic when exposed to radiation, the main parameter – radiation hardness criterion, is the low-level output voltage ("logical zero level", U_{OL}), which is determined by the saturation collector-emitter voltage of the output bipolar transistor (U_{CEsat}) [13]. When exposed to radiation, leading to radiation defect formation, the value of U_{CEsat} increases, primarily due to a reduction in the static current transfer coefficient h_{21E} of the output transistor and the lifetime of the charge carriers in its collector area. A sharp increase in U_{OL} occurs when the output transistor is no longer able to enter saturation mode due to the drop in h_{21}. This results in the IC's inability to perform basic logical functions, i.e., to discontinue its functioning. This is the reason why U_{OL} is used as a criterion for the radiation resistance of TTL-type logical elements.

Bipolar ICs were fabricated using V-groove isolation technology; the vertical transistor structure, along with the technology's special features, was described in [14].

The technological α-radiation source is a sealed plutonium (Pu) based radionuclide source in which, due to the α-decay, particles with an energy of ≈ 5 MeV are generated, having a silicon span of 20... 25 μm, i.e., capable of uniformly penetrating the active npn regions of structures. Irradiation of non-encapsulated IC α-structures with particles was carried out in a specially designed and manufactured laboratory facility using radioisotope sources. An overview of the technology and design of such sources, based on the relevant references, is given in [15].

Technological and test irradiation with relativistic electrons was carried out using a linear electron accelerator ELU-6 [8].

3.2. Statistical Evaluation of IC Radiation Hardness

Calculations of the U_{OL} Weighted Average Value and Dispersion were carried out by the method suggested in [16 pp. 43-44], using the approach proposed in [17 p. 28]. The probability density function calculation is necessary for determining the mathematical expectation, dispersion, and standard deviation parameters of a multimodal distribution. The probability density of a multimodal distribution (for example, 3 peaks) may be expressed in the form:

$$\begin{aligned} f_{probability\_density} &= K_{left\_peak}\cdot \\ &\cdot f_{left\_peak\_probability\_density} + \\ &\dots + K_{midway\_peak}\cdot \\ &\cdot f_{midway\_peak\_probability\_density} + \\ &\dots + K_{right\_peak}\, f_{right\_peak\_probability\_density}, \end{aligned} \tag{2}$$

$$K_{left\_peak} + K_{midway\_peak}\cdot + K_{right\_peak} = 1 \tag{3}$$

Coefficients k are computed as follows.

1. Calculation of the integral probability of detection of numerical value U_{OL} in the measurement range;
2. Calculation of the probability of detection of the numerical value U_{OL} close to each peak;
3. Calculation of the numerical value of the corresponding coefficient by dividing the result of 2 by the same of 1. Additional comments are located just near the calculations. Multimodal distribution parameters (mathematical expectation m, dispersion were calculated in a standard way, formulae (4), (5).

$$\begin{aligned} \mathrm{m} = \int_{U_{OL\_low}}^{U_{OL\_high}} \mathrm{f}_{probability\_density}(\mathrm{U_{OL}})\cdot \\ \cdot U_{OL}\, dU_{OL}, \end{aligned} \tag{4}$$

$$\begin{aligned} \int_{U_{OL\_low}}^{U_{OL\_high}} (U_{OL} - m)^2 \cdot \\ f_{probability\_density}(U_{OL}) dU_{OL} \end{aligned} \tag{5}$$

The U_{OL} integration limits are chosen in such a way that the probability of measuring the "logical zero" level is not equal to zero: $0.3 \leq U_{OL} \leq 0.4$ [V]. Symbols: normal (x; μ; σ) − normal distribution density, $f(x) = \frac{1}{(\sqrt{2\cdot\pi})\cdot\sigma}\, e^{-\frac{1}{2}\cdot\left(\left(\frac{x-\mu}{\sigma}\right)^2\right)}$, where μ is the mean; σ is the standard deviation; e is the base of the natural logarithm; π is the constant Pi; Logis (x; a; b) − the logistic distribution, $f(x) = \frac{1}{b}\cdot exp\left(-\frac{(x-a)}{b}\right)\cdot \left[1 + exp\left(-\frac{(x-a)}{b}\right)\right]^{-2}$ where a is the mean of the distribution, b is the scale parameter. Extreme distribution: $f(x) = \frac{1}{b}\cdot e^{-\frac{(x-a)}{b}}\cdot e^{-e^{-\frac{x-a}{b}}}$ where a is the threshold (location) parameter, b is the scale parameter.

4. Results of the Experiment after Test Irradiation by Electrons

The application of pre-radiation thermal treatment using 5.5 MeV electron irradiation ($\Phi_e = 2\cdot10^{16}$ cm^{-2}, isothermal annealing at 350 °C for 15 minutes) does not lead to a significant change in IC radiation resistance after the test electron irradiation with an energy of ≈ 5.5 MeV with *a dose ≈ of* $1.25\cdot10^{13}$*cm*$^{-2}$, except for a reduction of Dispersion by 15 %, which may be assumed as an approximate increase in radiation resistance.

The results of the radiation tests are shown in Table 2 and Fig. 2:

4.1. Comparison of the Radiation Resistance of ICs Manufactured by Standard Technology and the Application of Technological Irradiation by Electrons, α-particles, and Tested by γ-irradiation

The complex nature of U_{OL} dependencies after γ-irradiation (presence of extremes with different probabilities) requires the use of entropy analysis [18] to determine the efficiency of the application of different preliminary radiation-thermal treatment of IC (technological irradiation with α-particles or accelerated electrons with an energy of 5...6 MeV). Using the approaches proposed in [18, p.8], *probability distribution entropy H* is calculated by the formula (6):

$$H = -\sum_i P_{i_{peak}} \cdot log_2 P_{i_{peak}}, [bit], \qquad (6)$$

where $P_{i_{peak}}$ is the probability of the U_{OL} distribution peaks before and after test γ-irradiation for different (α, electron) technology and standard technology.

Table 2. Definition of the U_{OL} distribution parameters of a logic IC manufactured using Standard technology and technology, based on technological electron irradiation before and after test electron irradiation.

No.	Technology Type	Weighted average of U_{OL}, (U_{OL}), V	Dispersion, D, V^2
1.	Standard (before electron irradiation)	0.318	$9.183 \cdot 10^{-4}$
2.	Use of technological electron irradiation (before electron irradiation)	0.3222	$9.578 \cdot 10^{-4}$
3.	Standard (after electron irradiation)	0.32927	$7.053 \cdot 10^{-5}$
4.	Use of technological electron irradiation (after electron irradiation)	0.33289	$5.982 \cdot 10^{-5}$

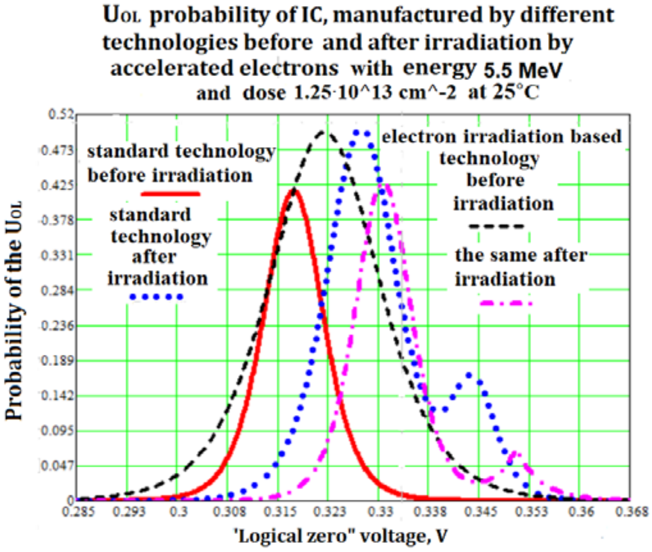


Fig. 2. The distribution of U_{OL} of IC, manufactured in accordance with the standard technology and based on the accelerated electron irradiation technology.

To compare the efficiency of IC radiation resistance enhancement technologies, considering the *continuity of distribution of U_{OL} probabilities*, the shape of which strongly depends on the physical nature of applied irradiation (α-particles or relativistic electrons) or its absence (standard IC technology), requires *differential entropy* ($H(X)$), formula (7) from [19, p. 87]:

$$H(X) = \int_{-\infty}^{\infty} f(x) \cdot log_2 f(x) dx, \qquad (7)$$

where *f(x)* is the probability distribution density of the X distribution.

However, in [18, pp. 25-26] it is stated that the discrete analog of formula (7) would be formula (8):

$$H = -\sum_i P_i \cdot log_2 P_i \cdot \Delta x \; [bit], \qquad (8)$$

Therefore, for the *continuous distributions* of U_{OL}, the differential entropy ***is proposed*** to be calculated by the formula (9) using the expressions for the *probability of* U_{OL}:

$$H(U_{OL}) = -\int_{U_{OL\_min}}^{U_{OL\_max}} P_i(U_{OL}) \cdot \log_2 \left(P_i(U_{OL})\right) dU_{OL}, \tag{9}$$

where $P_i(U_{OL})$ is a probability of the U_{OL} distribution in the measurement range ΔU_{OL}; $\left(\Delta U_{OL} = U_{OL\_max} - U_{OL\_min}\right)$ before or after test irradiation (γ–, relativistic electrons, etc.) for different (α, electron) technology irradiation types, as well as for the standard technology.

For example, for ICs manufactured by α-irradiation (Fig. 3, dark blue solid line), the differential entropy is equal to (10):

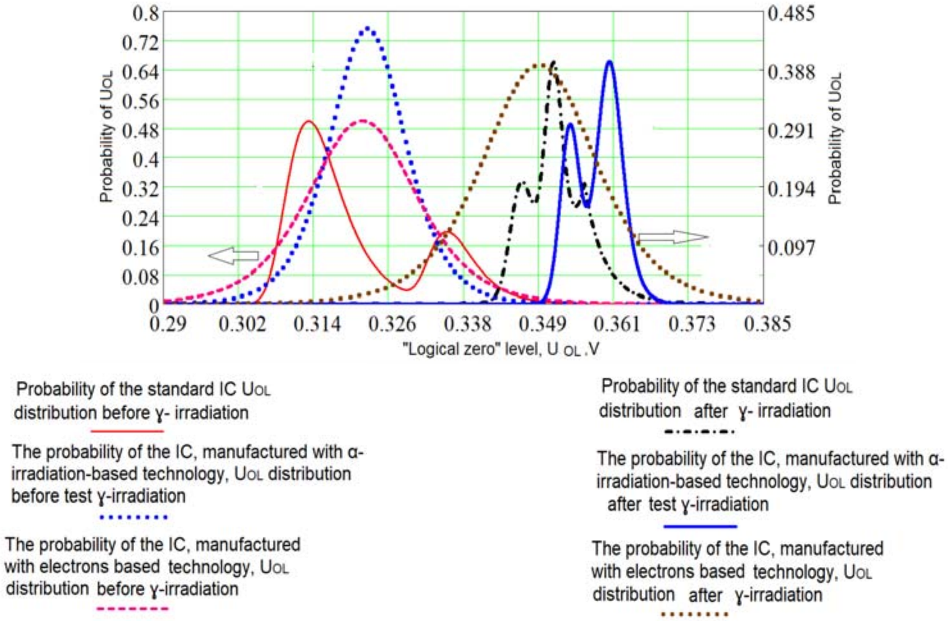


Fig. 3. Probability of "logical zero" level, U_{OL}, of IC, manufactured by different technologies, before (left axis) and after (right axis) γ-irradiation.

$$\begin{gathered} H_{\alpha\_technology\_\gamma\_test\_irradiation} = \cdot \\ = -\int_{0.3}^{0.4} (Probability_{\alpha\_irradiation\_based\_technology_{after}\_\gamma\_testing}(U_{OL}) \cdot \\ \cdot \log_2 Probability_{\alpha\_irradiation\_based\_technology_{after}\_\gamma\_testing}(U_{OL}))dU_{OL} = \\ = 6.93673 \cdot 10^{-3} \end{gathered} \tag{10}$$

Probability distribution entropy for IC manufactured with α-irradiation is equal to (11):

$$H\alpha = -\left(P_{left_{peak}} \cdot \log_2 P_{left_{peak}} + P_{right_{peak}} \cdot \log_2 P_{right_{peak}}\right) = 1.049 \tag{11}$$

The calculation results are shown in Table 3.

Let's designate the probability of IC sample failure as $Prob_F$ Prob_F, differential entropy as Diff_Ent, probability entropy as Prob_Entrop, then

$$Prob_F = 5.1336 \cdot 10^{-5} \cdot exp\begin{pmatrix}127.1193 \cdot \\ \cdot Diff\_Ent\end{pmatrix}, \tag{12}$$

$$Prob\_F = \frac{7.3668 \cdot 10^{-4}}{\left(1 + \left(\frac{\text{Prob\_Entrop}}{0.0455672}\right)^{2.148975}\right)} \tag{13}$$

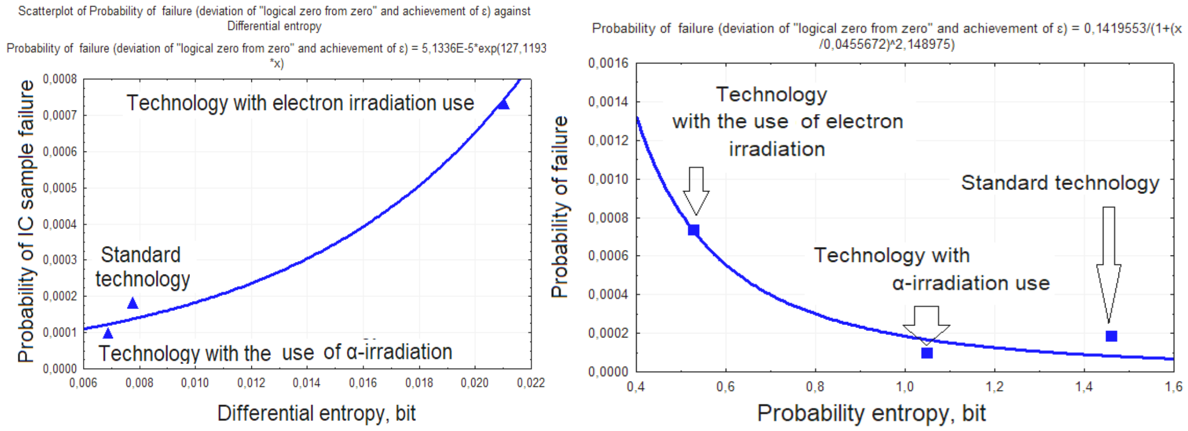
Experimental data visualization and approximation in Fig. 4, a), and comparing it with Fig. 3 (curves, numerical values of which are represented on the right axis) shows that increasing Diff_Ent for IC, manufactured with the use of technological accelerated electrons irradiation, results in an increase of the IC sample failure probability. For this technology, a "spreading" U_{OL} distribution with high dispersion is observed, leading to the rise in $H(U_{OL})$.

The formation after γ-irradiation of "compressed" multimodal distributions for ICs, produced by using standard technology (Fig. 3, black dashed-dot line) and technology with application of α-irradiation (Fig. 3, dark blue solid line), leads to an increase in *probability entropy* (Fig. 4, b) and a decrease in the probability of IC sample failure.

Increase of probability entropy *after* γ-irradiation is closely connected with its numerical value *before* testing, formula (14), model Bleasdale-YD, received by the use of [20], visualization is in Fig. 5.

Table 3. Summary of the γ-radiation test results of IC samples, manufactured by various types of preliminary radiation and thermal treatment, and standard technology.

No.	Parameter of the U_{OL} distribution	Type of technology					
		Standard technology		**Technology, based on *α-particles* irradiation**		**Technology, based on *electron* irradiation**	
		before γ-irradiation	**after γ-irradiation**	**before γ-irradiation**	**after γ-irradiation**	**before γ-irradiation**	**after γ-irradiation**
1.	Mathematical expectation, V	0.321	0.353	0.321	0.359	0.315	0.349
2.	Dispersion, V^2	$1.112·10^{-4}$	$2.897·10^{-5}$	$5.143·10^{-5}$	$1.533·10^{-5}$	$7.818·10^{-5}$	$1.173·10^{-4}$
3.	U_{OL} probability distribution entropy, bits	0.95982	1.461	0.314	1.049	0.498	0.529
4.	Differential entropy, bits	0.016	$7.787·10^{-3}$	0.015	$6.937·10^{-3}$	0.02	0.02105
5.	Probability of failure (ε = 0.4 V)	$6.947·10^{-4}$	$1.811·10^{-4}$	$3.214\ 10^{-4}$	$9.583·10^{-5}$	$4.886·10^{-4}$	$7.332·10^{-4}$



(a) (b)

Fig. 4. Dependence of the probability of IC sample failure of Differential, a), and Probability Entropy, b) for the devices, manufactured by the different technologies of preliminary radiation (α-particles irradiation, technological irradiation by accelerated electrons) and thermal treatment.

$$a = 6.67378·10^{2};\ b = 3.1399764·10^{-2};\ \theta = -1.6390775·10^{1},$$

$$\begin{aligned} & Probability\_entropy\_after\_\gamma\_irradiation = \\ & = Probability\_entropy\_before\_\gamma\_irradiation \cdot \\ & \cdot (a + b \cdot Probability\_entropy\_before\_\gamma\_irradiation^{\theta})^{-\frac{1}{\theta}} \end{aligned} \tag{14}$$

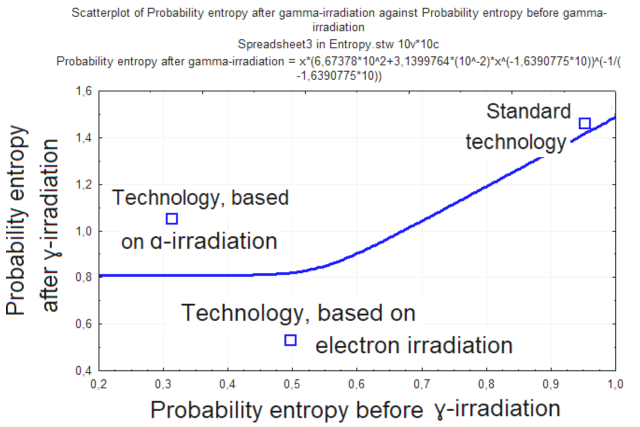


Fig. 5. Connection of the probability entropy before and after γ-irradiation for ICs, manufactured by different technologies.

Increasing standard technology IC distribution complexity of "logic zero level", which is expressed by the bimodal distribution of U_{OL} before test irradiation (Fig. 3, solid red line), leads to a significant increase in probability entropy after γ-irradiation and thus reduces the numerical value of IC sample probability failure (Fig. 4, b). This effect requires further analysis, for example, to determine whether it is present in IC samples, manufactured with preliminary radiation-thermal treatment and having a bimodal distribution of U_{OL} before test irradiation.

5. Conclusions

1. Preliminary radiation and thermal treatment of IC as a part of their technology has a strong influence on the radiation resistance of manufactured products, although this effect is unique for various combinations of technological and test experimental irradiation. For example, in the case of IC testing carried out with accelerated electrons (with energy ≈ 5…6 MeV), and if the IC sample is manufactured using α-particle irradiation, an improvement in radiation hardness up to 40 times is observed. The improvement in rad-hardness is limited to 15 % when relativistic electrons are employed for technological irradiation.

2. The complex nature of U_{OL} dependencies after γ-irradiation (presence of extremes with different probabilities) requires the use of *entropy analysis* to determine the efficiency of the application of different preliminary radiation-thermal treatment of IC. This method of analysis shows that technology based on preliminary electron irradiation may be a major cause of high-probability IC sample failure.

3. For the *continuous distributions* of U_{OL}, the differential entropy ***is proposed*** to be calculated by the formula (9), using the expressions for the ***probability*** *of IC* U_{OL}.

4. Distribution complexity of "logic zero level" before test irradiation, improving radiation hardness of the standard technology sample, requires further analysis to determine whether this effect is present in IC samples, manufactured with preliminary radiation-thermal treatment and having a bimodal distribution of U_{OL} before test irradiation.

References

[1]. I. M. Vishnevs'kij, G. P. Gajdar, O. V. Kovalenko, et al., Radiation and Nuclear Technologies at the Institute for Nuclear Research of the NAS of Ukraine, *PAT VYPOL*, 2014 (in Ukrainian).

[2]. T. Kovalinska, Using ionized irradiation in radiation technologies, Dr. Sci. Thesis, Institute for Nuclear Research, *National Academy of Sciences of Ukraine*, Kyiv, 2021 (in Ukrainian).

[3]. M. H. O. Sampa, N. M. Omi, C. S. Rela, D. Tsai, Potential and Future Trends on Industrial Radiation Processing Technology Application in an Emerging Country – Brazil, *IPEN-CNEN Radiation Technology Center*, 2006.

[4]. Z. Zimek, Application of radiation technologies for the modification of electronic devices, in Applications of Ionizing Radiation in Materials Processing (Y. Sun, A. G. Chmielewski, Eds.), *Institute of Nuclear Chemistry and Technology*, 2017.

[5]. J. M. Obodovsky, Physical Basis of Radiation Technologies: Training Manual, *Intelligence*, 2014.

[6]. N. A. Poklonsky, et al., Investigation of Transient Processes in Semiconductor Structures: Manual, *Belarusian State University*, 2009.

[7]. P. B. Lagov, A. S. Drenin, A. A. Meshcheryakov, et al., Application of radiation-thermal treatment to suppress sensitivity of silicon microcircuits to single radiation effects, *Rocket-Space Device Engineering and Information Systems*, Vol. 8, Issue 3, 2021, pp. 99-103.

[8]. S. Bytkin, Deceleration of the "logical zero" (U_{OL}) degradation of bipolar logic IC, manufactured using preliminary radiation and thermal treatment, in *Proceedings of the 7th International Conference on Microelectronic Devices and Technologies (MicDAT'25)*, 2025, pp. 11-21.

[9]. I. F. Seliverstova, Limit Theorems of Probability Theory: Textbook, *Academy of Natural Science*, 2019 (in Russian).

[10]. E. A. Vanina, E. M. Veselova, V. A. Rokosey, Ordering of Radiation Defects in Inorganic Systems: Monograph, *Amur State University Publishing House*, 2014 (in Russian).

[11]. V. A. Labunov, N. T. Kvasov, V. I. Yarmolik, et al., Formation of complex radiation defects in irradiated materials, *Doklady of the National Academy of Sciences of Belarus*, Vol. 65, Issue 3, 2021, pp. 275-280 (in Russian).

[12]. V. I. Varnina, A. A. Groza, P. G. Litovchenko, et al., Effects of self-organization of radiation defects in silicon irradiated with high-energy light ions, in *Proceedings of the 9th International Conference "Interaction of Radiation with Solids"*, 2011, pp. 110-112.

[13]. E. N. Vologdin, A. P. Lysenko, Radiation Effects in Integrated Circuits and Methods for Testing Semiconductor Electronics Products for Radiation Resistance, Textbook, *Moscow State Institute of Electronics and Mathematics*, 2002.

[14]. S. V. Bytkin, T. V. Krytskaya, Nonlinear effect of Ge concentration on the test npn ICs transistors structures gain (β) and percentage of yield of suitable products, in *Proceedings of the 5th International Conference on Microelectronic Devices and Technologies (MicDAT'23)*, 2023, pp. 5-11.

[15]. S. V. Bytkin, T. V. Kritskaya, Methodology for modeling experimental results of α-particle irradiation of test NPN IC structures in the OriginPRO computational environment, in Electronic Devices and Technologies For Industry, Energy Saving and Environmental Areas: Monograph (T. V. Kritskaya, et al., Eds.), *Oldi+*, 2023.

[16]. S. Bytkin, Assessment of the planar low power discrete *npnp* structure radiation hardness under γ-irradiation, taking into consideration non-linear change of the holding current probability, *Sensors & Transducers*, Vol. 267, Issue 4, 2024, pp. 34-48.

[17]. R. N. Vadzinsky, Reference Book on Probability Distributions, *Nauka*, 2001 (in Russian).

[18]. O. V. Tsvetkov, Entropy Analysis of Data in Physics, Biology, and Technology, *Saint Petersburg Electrotechnical University "LETI"*, 2015.

[19]. A. I. Mithuhin, Applied Information Theory: Teaching and Methodological Manual, *Belarusian State University of Informatics and Radioelectronics*, 2018.

[20]. CurveExpert Basic, An easy-to-use curve fitting system for Windows, Daniel G. Hyams, 2020, http://www.curveexpert.net