Using probabilistic fuzzy models for the prediction of functional failures of microwave LSI with radiation exposure

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Abstract. The article presents an analysis of microwave LSI behavior under radiation exposure at the functional-logical level of description. The analysis is based on fuzzy digital automaton and topological probabilistic models of workability assessment. It is shown that in certain cases both deterministic and non-deterministic failures are typical. Each operation threshold in logic elements under radiation influence has a zone of uncertainty and can be expressed quantitatively by a fuzzy number. This case, the real nature of microwave LSI radiation behavior is determined by the specific ratio of radiation-sensitive parameters of its elements and by taking into account the influence of their statistical scatter. Methods are proposed for simulating failures of microwave LSI under radiation exposure that are based on the model of a fuzzy digital Brauer automaton and a probabilistic reliability automaton.

1 Introduction

In some cases microwave LSI operation under radiation exposure is determined by a statistical dispersion of the threshold failure levels for the same type of samples. Under the influence of radiation the model of a digital automaton involving probability theory tools is used. This case for Boolean reliability networks using models of LSI internal elements in the state space, where the Boolean lattice axioms are fulfilled [1]. In case when it is necessary to take into account the physical mechanisms of the LSI failure, design of a functional-logical model implies a transition from the the Boolean lattice axiomatics to the vector lattice axiomatics with the corresponding replacement of algebraic operations for the “minimum”, “maximum” and “complement” operations for each $x \in X$ [2]. Thus, the actual nature of LSI radiation behavior is determined by a specific ratio of radiation-sensitive parameters of its elements, taking into account the spread influence. Note that the relation between the probability density distribution function of the of the spread and the criterion membership function (CMF) determines ultimately the expediency of using functional-logical models of LSI radiation behavior in each specific case. It should be considered that the parameters of the distribution functions characterizing uncontrolled statistical factors are themselves dependent on radiation. Moreover, the nature of their

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changes during irradiation depends on many factors, including the type of radiation, its intensity and spectrum, the type of criterion parameter characterizing the radiation resistance of the LSI and operation mode of the microcircuits. Therefore, in different ranges Moreover, the nature of their changes during irradiation depends on many factors, including the type of radiation, its intensity and spectrum, the type of criterion parameter characterizing the radiation resistance of the LSI and operation mode of the microcircuits. Therefore, in different ranges of levels or intensities of radiation exposure, the LSI model can be either fuzzy or probabilistic.

2 Modeling environment

Let m branches come out of the node n . Then the multiplicity of a node during normal operation is equal to m [1]. When exposed to external factors (radiation, microwave radiation, etc.), the thresholds for the triggering of logical elements associated with the node under consideration $l_{nj}, j=1, 2, \dots, m$ begin to degrade. In addition, the amplitude levels of logical zero and unity (U^0, U^1), change, which leads to a decrease in the pulse l_n . Thus, the performance of the circuit depends on the magnitude of the excess

$$\Delta_{nj} = l_n - l_{nj}$$

In this case, each threshold has a zone of uncertainty, in which the logical element begins to switch randomly and the multiplicity of the node becomes uncertain and can be quantitatively expressed as a fuzzy number.

In this paper, as in [2-5], we use triangular $L - R$ numbers, which greatly simplifies the estimates.

The zone of uncertainty, l_n, l_{nj}^n are random values. Therefore, to simplify the task, the further calculations will use the maximum value of the uncertainty zone $q_{lj \max}$ for each branch, which is determined experimentally and can be used by default while creating a CAD system. In [2, 6], when determine the fuzzy multiplicity number, the distribution of quantities l_n only was considered. In fact, the values l_n, l_{nj}^n change simultaneously with the change in the absorbed dose of radiation.

Let, $\Delta_{nj} \rightarrow q_{lj \max}$ then the mode of a fuzzy number is determined by the probability of exceeding Δ_{nj} of the number $q_{lj \max}$, that is $P(\Delta_{nj} > q_{lj \max})$. The blurring of a fuzzy number obviously depends on $P(\Delta_{nj} < q_{lj \max})$. The laws of the distribution of numbers l_n and l_{nj} denote, respectively, $F_n(x)$ and $G_j^n(x)$, i.e.

$$\begin{cases} F_n(x) = P(l_n < x) = \int_{-\infty}^x f_n(\xi) d\xi \\ G_j(x) = P(l_{nj} < x) = \int_{-\infty}^x g_j(\xi) d\xi \end{cases}, \quad (1)$$

Given the specific conditions of solving the system, we can assume:

$$f_n(x) = \begin{cases} 0 & \\ \text{convex differentiable function}, & 0 < x \leq 1 \\ 0, & x > 1 \end{cases}$$

$$g_j(x) = \begin{cases} 0, & x \leq 0 \\ \text{convex differentiable function}, & 0 < x < 1 \\ 0, & x > 1 \end{cases}$$

Graphs of distribution densities described by expression (1) are shown in Fig. 1.

Fig. 1. Density distribution of values l_n и l_{nj} : $\epsilon_{l_{nj}}$ - expectation l_{nj} , ϵ_{l_n} - expectation l_n .

With an increase in the dose of radiation, the function $g_j(x)$ shifts to the right and $f_n(x)$ to the left. In this case, the excess Δ_{nj} decreases and has its own distribution, which can be taken as a criterial function, as a fuzzy probability.

We denote the excess probability distribution density Δ_{nj} by $\delta_{nj}(x)$.

Then

$$\int_{-\infty}^{\infty} \delta_{nj}(x) dx = 1, \quad (2)$$

Considering the previously imposed restrictions on the functions and, equality (2) takes the form:

$$\int_0^1 \delta_{nj}(x) dx = 1. \quad (3)$$

As shown by the experimental data in Fig. 2, 3 distributions f_n and g_j are close to the normal law [7-10].

The analysis of the LSI radiation behavior shows that, in some cases, for failures in terms of both functional and electrical parameters, there is a significant statistical variation in the threshold of failure levels for similar types of samples. At the same time, a decrease in the dispersion of the variation of the failure threshold during irradiation was observed with the volume effects of displacement in bipolar structures (Fig. 2), the radiation sensitivity of which is determined by the change in the lifetime.

At the same time, with respect to dose effects in CMOS LSI structures, there is most often a reversal of the dependence of the dispersion on the level of radiation (Fig. 3).

Therefore, in different ranges of exposure levels, an object model can be both fuzzy and probabilistic [11].

Fig. 2. The distribution of averaged over the plate static current transfer ratio of the base (B_N) 30 bipolar ADS (advanced low power Schottky) transistors test structure 556PT7 between 10 plates of the same batch with different electron fluence: 1 - $F_e=0$, 2 - $F_e=10^{14}$ e/cm², 3 - $F_e=5 \cdot 10^{14}$ e/cm², 4 - $F_e=10^{15}$ e/cm² ($j=10^2$ A/cm², $S_{3M}=12 \cdot 12=144$ micron², $E_e=5$ MeV).

Fig. 3. Distribution of averaged U_{OUT}^0 CMOS chip LSI RAM 1617PY6 dose of (1), Uthr n-channel and p-channel MOS transistors (2, 3), obtained at an electron accelerator with $E=130$ keV.

With reference to the normal distribution law, formula (3) can be rewritten in the form:

$$\delta_{nj}(x) = \frac{1}{2\pi\sigma_n \cdot \sigma_{nj}} \int_0^{1-x} e^{-\left[\frac{(\xi - \varepsilon_n)^2}{2\sigma_n^2} + \frac{(x + \xi - \varepsilon_{nj})^2}{2\sigma_{nj}^2}\right]} d\xi,$$

where σ_n и σ_{nj} - are the dispersions f_n and g_j , ε_n and ε_{nj} are shown on figure 1.

After the transformations, the resulting expression will take the following form:

$$\mu_n^j = \frac{1}{\sqrt{2\pi} \sqrt{\sigma_n^2 + \sigma_{\Pi j}^2}} e^{-\frac{\sigma_\Sigma^2 (\varepsilon_n - \varepsilon_{\Pi j} + x)^2}{2}}, \quad (4)$$

$$\sigma_\Sigma = \frac{\sigma_n \cdot \sigma_{\Pi j}}{\sqrt{\sigma_n^2 + \sigma_{\Pi j}^2}}.$$

If we express the integral (4) in terms of integrals of probabilities, we finally get:

$$\mu_n^j = \int_{\varepsilon_n - \varepsilon_{\Pi j} + x}^{\varepsilon_n - \varepsilon_{\Pi j} + x} \Phi\left(\frac{\varepsilon_n - \varepsilon_{\Pi j} + x}{\sigma_\Sigma}\right) d\varepsilon_n, \quad (5)$$

where - $\Phi(z) = \int_{-\infty}^z \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$, $\Phi(z)$ - is the integral of probability.

The function turns out to be monotonously decreasing while x is changing from “0” to “1”. Then the probability $P(x < q_{\Pi j \max})$ is

$$P(x < q_{\Pi j \max}) = \int_0^{q_{\Pi j \max}} \mu_n^j dx, \quad (6)$$

Formulas (5) and (6) allow us to find the parameters of the desired fuzzy number n of a node multiplicity: mod_n and blur σ_{r_n} . For a normal distribution law, the parameters of a fuzzy number are as follows:

$$\text{mod}_n = \sum_{j=1}^m \mu_n^j q_{\Pi j \max},$$

$$\sigma_n = \sum_{j=1}^m \mu_n^j q_{\Pi j \max}^2,$$

$$P(x > q_{\Pi j \max}) = \mu_n^j \left[\Phi\left(\frac{\varepsilon_\Sigma}{\sigma_\Sigma}\right) + \Phi\left(\frac{1 - q_{\Pi j \max} - \varepsilon_\Sigma}{\sigma_\Sigma}\right) \right], \quad (7)$$

$$\mu_n^j = \frac{1}{\sqrt{2\pi} \sqrt{\sigma_n^2 + \sigma_{\Pi j}^2}} e^{-\frac{\sigma_\Sigma^2 (\varepsilon_n - \varepsilon_{\Pi j} + x)^2}{2}},$$

Each branch emanating from an n node generates fuzzy numbers in the corresponding nodes of higher rank in the tree. In this case, it is necessary to take into account some degradation of the pulse at the output of the corresponding logic element. After such an account of the pulse state, the components of formula (7) are summed over all nodes of the critical tree, which gives the integral criterion of radiation resistance in the form of the tree power spectrum.

Another approach to estimating stability with fuzzy numbers is possible, that deals with fuzzy numbers for each node branch. In this case, the logic of elements, working with fuzzy impulses, becomes fuzzy. It helps to identify system failures and bottlenecks, by analogy with the Monte Carlo method.

3 Conclusion

Ensuring the stability of the LSI under ionizing radiation exposure is determined by the specific tree spectrum of the LSI topology and the ratio of radiation-sensitive parameters: the multiplicity of nodes, the power of the tree spectrum, the mode of a fuzzy number. In this case, the ratio between the distribution function of the spread and the fuzzy number mode determines, ultimately, the expediency of using functional logical models of the LSI behavior for each specific case. Such a comparison is a necessary step in the general procedure for analyzing the radiation stability of an LSI. It should be noted that in different ranges of levels or intensity of exposure, the power estimate of the LSI topology tree spectrum can be both fuzzy and probabilistic. At the same time, the fuzzy multiplicity can be specified in n -dimensional space with preservation of the basic parameters of the model, and the radiation effects occurring in the LSI at different radiation levels are evaluated in it by changing the same system parameter. Such a model structure is probabilistically fuzzy with probabilistic type operators, and the criterion membership function is a superposition of the statistical and deterministic criterion-membership function. At the same time, the interrelation of fuzzy multiplicity and probabilistic logic was defined, which makes it possible to most accurately quality estimates of the LSI functioning under the influence of radiation.

References

1. Frank M.J., *Associativity in a class of operations on spaces of distribution functions Aequationes Math* v. **12**, pp. 121-144 (1975)
2. V.M. Barbashov, N.S. Trushkin, *Evaluation performance of digital integrated circuits while exposed to radiation*, IOP Conf. Ser. : Mater. Sci. Eng. 151 012011 (2016)
3. V.M. Barbashov, B.I. Podlepetsky, N.S. Trushkin, *Simulation of the radiation reliability of digital devices at the functional and logical level*, Sensors and systems, v. **4**, pp. 54-57 (2016)
4. Gretzer G., *General theory of lattices* M, Mir, 456 p (1982).
5. Yager R.R. *Fuzzy sets and theory of possibilities* (M., Radio and communication (1982)
6. Pospelov D.A., *Fuzzy sets in control and artificial intelligence models* (M., Science, 1986)
7. Denisenko V.V., *Compact models of MOS transistors for SPICE in micro- and nanoelectronics* (M., FIZMATLIT, 2010)

8. V.M. Barbashov, N.S. Trushkin, *Functional and logical modeling of the quality of functioning of the IC under the influence of radiation and electromagnetic radiation*, Microelectronics, v. **38**(1), pp. 34-47 (2009)
9. A.V. Sogoyan, A.I. Chumakov, A.Yu. Nikiforov *Method for Predicting CMOS Parameter Degradation Due to Ionizing Radiation with Regard to Operating Time and Conditions*, Russian Microelectronics, v. **28**(4), pp. 224-235 (1999)
10. V. M. Barbashov, N.S. Trushkin and O. A. Kalashnikov, *Deterministic and nondeterministic failure models of LSI circuits exposed to radiation*, Russian Microelectronics, v. **44**(5), pp. 312-315 (2015)
11. A. V. Sogoyan, and V. A. Polunin, *A model for the formation of leakage currents in the dielectrics of MOS structures under the effect of heavy charged particles*, Russian Microelectronics, v. 44(1), pp. 54-59 (2015)