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METHOD FOR INTEGRATED CIRCUITS TOTAL IONIZING DOSE HARDNESS TESTING BASED ON COMBINED GAMMA- AND X-RAY IRRADIATION FACILITIES

Armen V. Sogoyan[1,2], Alexey S. Artamonov[1,2], Alexander Y. Nikiforov[1,2], Dmitry V. Boychenko[1,2]

[1]National Research Nuclear University MEPhI, Moscow, Russia
[2]JSC "Specialized electronic systems" (SPELS), Moscow, Russia

Abstract. *A method is proposed to test microelectronic parts total ionizing dose hardness based on a rationally balanced combination of gamma- and X-ray irradiation facilities. The scope of this method is identified, and a step-by-step algorithm of combined testing is provided, along with a test example of the method application.*

Key words: *microelectronics, TID effects, gamma- ray, X-ray*.

1. INTRODUCTION

Testing procedure of microelectronic parts, i.e., integrated circuits (ICs), semiconductor devices, solid-state microwave electronics and electronic modules for compliance with nuclear and space radiation hardness regulations can be based on various radiation facilities that initiate total ionizing dose (TID) effects [1], [2] in devices under test (DUT).

Since the problem of radiation testing of microelectronic parts had arisen for the first time and till now, TID effects are induced in laboratory mainly by gamma irradiation test facilities based on Co^{60} sources. Every isotope-based gamma irradiation facility is unique and complex installation with a full-scale biological personnel protection, commonly designed under dedicated projects.

There are also some other types of TID radiation test facilities which are widely used such as electron accelerators, other isotopic sources (Cs^{137}), nuclear reactors. In all cases radiation test installation is focused at reproducing characteristics equivalent to real-world radiation factors and their effects.

As gamma quanta have high energy (about 1 MeV), this results in high penetrating power and weak dependence of the total ionizing dose in active areas of DUT. At the same time in order to provide radiation safety gamma irradiation facilities require a

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Corresponding author: Aleksandr Y. Nikiforov
National Research Nuclear University MEPhI, Moscow, Russia
(e-mail: aynik@spels.ru)

significant (usually from 6 up to 25 meters) signal lines distance from DUT to the measuring hardware. This remote measurements usually fail to test all necessary modes and conditions of DUT operation under irradiation. Moreover a substantial part of DUT informative parameters (including those related to precision and high frequency performance) have become totally immeasurable at such a distance. Gamma irradiation facilities have low general availability due to strict radiation safety regulations and it is impossible to use such a facility directly within IC design and manufacture process. As a result, such method of testing has not a very compelling business case in its favor.

To overcome this downside of gamma irradiation facilities, in late 80s to early 90s new TID simulation test method have been developed using relatively compact X-ray irradiators with low-energy (10...100keV). In tests with X-ray facilities, intensity is tuned so as to result in a tantamount change in parameters, faults and failures of electronic components compared to the real-world ionization sources having the same dominant effect. X-ray testers (e.g., produced by Aracor, USA or SPELS, Russia) have been installed in many companies specialized in microelectronics research and development. The main goal of X-ray testers is their radiation safety (2 mm iron shield is enough for 10 keV source) together with very short signal lines (less than 1 meter) and good compatibility with automotive control and measurement tools (including wafer probes).

Implementation of X-ray testers for microelectronics TID hardness was accompanied by theoretical and experimental verification and research to substantiate equivalence of TID effects of various types of radiation [3]-[11]. As a result X-ray testers were incorporated into microelectronic processes and test standards [12], [13].

2. USE OF X-RAY IRRADIATION FACILITIES

The main issue restraining application of X-ray testers is their low energy and, consequently, low penetration of X-ray radiation, as well as substantial dependence of TID absorbed in active areas, on design and process specifics of DUT. All these necessitate advanced expert skills to ensure quantitative TID assessment (i.e. dosimetric evaluation) in the context of process diversity of microelectronic parts, a multitude of packages used, etc.

A substantial number of microelectronic parts tested today are sophisticated chips used in modern apparatus. Test customers tend to minimize the number of tested samples of each type to 3...5. Many types of microelectronic parts have plastic packages. Dosimetric evaluation of such samples is rather complex, because in most cases the manufacturer fails to provide data on the component design, layout, process used, chemistry of the package, etc.

Therefore, in this work we tried to overcome the disadvantages of gamma and X-ray radiation test sources specifically for microelectronics TID research using the inherent benefits of both of them in favor of compact and safe X-ray source and rationally minimizing usage of gamma-sources for necessary cases only.

3. SCOPE OF JOINT TESTING

The joint method of TID hardness testing based on gamma- and X-ray irradiation facilities has been designed to enhance precision and quality of X-ray based simulation testing defined in [13]. It covers packaged and caseless silicon-based CMOS circuits (i.e., with monosilicon, epitaxial, silicon-on-sapphire and silicon-on-insulator structures), as well as bipolar and BiCMOS (including SiGe) ICs.

To be admitted to tests, microelectronic parts have to meet the following conditions:

- number of samples: 3 or more
- samples taken from the same production lot, with clearly identified samples.

4. CALIBRATION METHOD

In X-ray dosimetry the method of calibration is commonly used. The most TID sensitive parameter of the device under test is chosen as a calibration parameter and denoted as q_k. It is assumed that the X-ray dose is equivalent to the γ radiation dose (D_γ), if they both produce an identical radiation-induced change in the calibration parameter under identical testing conditions (mode, temperature, time from start of irradiation till measurement): $D_э(q_k) = D_\gamma (q_k)$.

$D_\gamma(Q_k)$ is called the calibration curve; it is determined based on the test results on a gamma irradiation facility. Based on this curve, the tested sample TID sensitivity is "calibrated".

As calibration parameter q_k, we propose to choose such electrical parameter of the product, the radiation-induces change of which is determined by TID effects. Additional requirements to be met by the calibration parameter are: ease of measurement, a higher sensitivity to D_γ and a long linear or, at least, "smooth" monotonous interval with $q_к=q_к(D_\gamma)$, lower susceptibility to electromagnetic interference and crosstalk.

5. ALGORITHM OF COMBINED TESTING

Microelectronics TID hardness testing procedure on gamma and X-ray facilities is based on the following algorithm.

1. Predicting the level of TID hardness and selection of the most sensitive operating mode.

The following prediction methods can be used (descending priority):

- Based on the lab's own previous experience in testing of a given part type, or other products of a given manufacturer;
- Based on formally published results of previous testing of a given part type or other products of a given manufacturer provided by another test labs;
- Based on formally published results of previous tests of similar parts provided by a given manufacturer, including technical specifications;
- Based on results of previous tests of functionally similar parts provided by other various manufacturers;
- Based on, data-bases, articles, advertizing and other informal sources.

Such a prediction results in a preliminary selection of a particular calibration parameter from various device under test (DUT) parameters listed in the test procedure as well as selection of the mostly TID-sensitive electric and operating modes.

If there is no technical evidence in favor of a particular electric mode, we recommend opting for the mode with a maximum supply voltage according to specifications.

2. Analysis of DUT design and estimation of the X-ray package (coating) attenuation ratio.

The attenuation ratio is estimated based on the type, thickness and chemical composition of the package (protective coating) of a DUT.

3. X-ray irradiation of DUT sample, measuring all the criterial parameters specified in the test procedure, in the selected operating mode under the normal climatic conditions. To make a preliminary selection of the calibration parameter and the criterial parameters, the $q = q(D_X)$ dependency should be identified.

The power of X-ray radiation absorbed on the crystal surface, based on the estimated attenuation ratio, should fall in the range of X-ray irradiation facility power used for calibration. Irradiation proceeds until the sample fails in most of criterial parameters, or until the level of exposure at which radiation-induced change of a pre-selected calibration parameter and criterial parameters 100 times exceeds the measurement error. When choosing an irradiation mode, the following condition should be met: $t_{rad} > 10 \cdot t_{meas}$, where t_{rad} is the full exposure time, t_{meas} – total time of parameter measurement during irradiation.

In case of low radiation sensitivity of the calibration parameter and other criterial parameters (initial value changes less than 100 times the measurement error) hardness is assessed on a smaller number of samples (but still 2 samples at least) on a gamma irradiation facility.

4. Gamma irradiation of a DUT sample, measuring all the criterial parameters in the selected operating mode under the normal climatic conditions. To make a preliminary selection of the calibration parameter and the criterial parameters, the $q = q(D\gamma)$ dependency should be identified.

The power of gamma radiation absorbed should fall in the range 0.5...2.0 of gamma radiation absorbed on the crystal surface, in view of the estimated attenuation ratio.

Irradiation continues until $D\gamma_0$ is reached, or the sample fails in most of criterial parameters, or until the level of exposure at which radiation-induced change of a pre-selected calibration parameter and criterial parameters 100 times exceeds the measurement error. The TID is measured by the gamma irradiation facility standard dosimetric methods. When choosing an irradiation mode, the following condition should be met: $t_{rad}>10 \cdot t_{meas}$, where t_{rad} is the full exposure time, t_{meas} is the total time of parameter measurement during irradiation.

5. Comparative analysis of X-ray and gamma irradiation test results. A decision is made on feasibility and validity of X-ray tests and the calibration factor is estimated.

6. APPLICABILITY OF COMBINED TESTING

The method of joint testing is applicable in case it is possible to build the calibration transformation:

$$D_\gamma = kD_X \,, \tag{1}$$

where k is a factor for which dependencies $q_k(D_X)$ and $q_\kappa(D_\gamma)$ are approximately similar:

$$\max_{D_\gamma}\left|\frac{q_{kX}(D_\gamma / k)-q_{k\gamma}(D_\gamma)}{q_{k\gamma}(D_\gamma)}\right| < \sqrt{0.04+\delta^2}\ , \tag{2}$$

where δ is a relative instrumental error for q (according to the measurement tool data sheet), $q_{k\gamma}(D_\gamma)$ is the dependence of criterial parameter versus D_γ obtained on the gamma irradiation facility (item 4), $q_{kX}(D_X)$ is the dependence of the criterial parameter increment versus the exposure level D_X on the X-ray irradiation facility (3). The k-factor in the relationship (1) can be estimated by the least squares method. Condition (2) should be verified at least at two points of $D\gamma$. When condition (2) is met, a decision on applicability of calibration-based dosimetry method is taken.

Lot #1 of n_γ samples is tested on a gamma irradiation facility, and lot #2 of n_X samples is tested on an X-ray irradiation facility, where $n_X > n_\gamma$. Both lots are tested in an identical electric mode and under the same climatic conditions.

The method to estimate the k-factor depends on the nature of functions $q_{\gamma i}(D_\gamma)$, where i is the number of a sample in lot 1: $i = 1 \ldots n_\gamma$.

As a calibration parameter, we recommend to select a one with the higher relative radiation-induced increment. If there are multiple criterial parameters having close relative increment values (within 20%), the conditions outlined below apply to each parameter.

If, in the TID range $0 \ldots D_{\gamma 0}$, the $q_{\gamma i}(D_\gamma)$ dependency has a maximum in the neighborhood of $D_{\gamma i max}$, it is normalized to the value of $q_{\gamma i\ l}$, measured at $D_{\gamma i\ l}$ closest to $D_{\gamma i max}$. If, within a dosage range of $0 \ldots D_{\gamma 0}$, the $q_{\gamma i}(D_\gamma)$ dependence has several maximums, the main maximum should be selected. If no maximum is available, the dependency is not normalized.

The calibration level of q_0 is selected. The calibration level should be selected close to the value corresponding to the parameter tolerance boundary specified for the tested sample.

For the j-th sample of lot 1, $j = 1 \ldots n_\gamma$, based on the experimental dependency $q_{\gamma i}(D_\gamma)$ the value of TID $D_{\gamma j}$ is determined from condition

$$\left|\frac{q_{\gamma\ j}(D_{\gamma\ j})-q_0}{q_0}\right| < \delta \tag{3}$$

If necessary, to determine $D_{\gamma j}$ from (3), linear interpolation of dependency $q_{\gamma j}(D_\gamma)$ can be used. Similarly, the values of D_{Xi}, $i = 1 \ldots n_X$, for lot 2, are defined.

Then, the point estimate of calibration factor k is made:

$$k = \frac{\overline{D_\gamma}}{\overline{D_X}}\ , \tag{4a}$$

$$\overline{D_X} = \frac{1}{n_X}\sum_{i=1}^{n_X} D_{Xi}\ , \tag{4b}$$

$$\overline{D_\gamma} = \frac{1}{n_\gamma}\sum_{i=1}^{n_\gamma} D_{\gamma i} \tag{4c}$$

When there are multiple criterial parameters with close relative values of increments, the calibration parameter is that for which

$$\delta = \sqrt{\delta_X^2 + \delta_\gamma^2} \equiv \sqrt{\frac{1}{n_X}\frac{\sum_{i=1}^{n_X}(D_{Xi}-\overline{D_X})^2}{\overline{D_X}^2} + \frac{1}{n_\gamma}\frac{\sum_{i=1}^{n_\gamma}(D_{\gamma i}-\overline{D_\gamma})^2}{\overline{D_\gamma}^2}} \tag{4d}$$

has the smallest value.

The lower boundary k_L of the calibration factor confidence interval is calculated:

$$k_L = \frac{k-\sqrt{Q_1 k^2 + Q_2 - Q_1 Q_2}}{(1-Q_1)}, \tag{5}$$

$$Q_1 = \frac{t_{1-\frac{\alpha}{2},n_X+n_\gamma-2}}{(n_X+n_\gamma-2)}\left(\frac{1}{n_X}+\frac{1}{n_\gamma}\right)\frac{\sum_{i=1}^{n_X}(D_{Xi}-\overline{D_X})^2}{\overline{D_X}^2},$$

$$Q_2 = \frac{t_{1-\frac{\alpha}{2},n_X+n_\gamma-2}}{(n_X+n_\gamma-2)}\left(\frac{1}{n_X}+\frac{1}{n_\gamma}\right)\frac{\sum_{i=1}^{n_\gamma}(D_{\gamma i}-\overline{D_\gamma})^2}{\overline{D_X}^2}$$

where $t_{1-\alpha/2,N}$ is the quantile of the Student distribution with N degrees of freedom, where confidence level is $\alpha/2$. Confidence Level $P=1-\alpha$is defined in the regulatory and technical documentation. If its value is not set, it is assumed to be 0.95 according to radiation test standards. As the calibration factor $K=k_L$ is taken.. The $k/k_L > 1$ ratio plays the role of testing norm which depends on the number of samples tested. A relative dosimetry error in such a case Δ is affected by relative errors of gamma (Δ_γ) and X-ray (Δ_X) dosimetry:

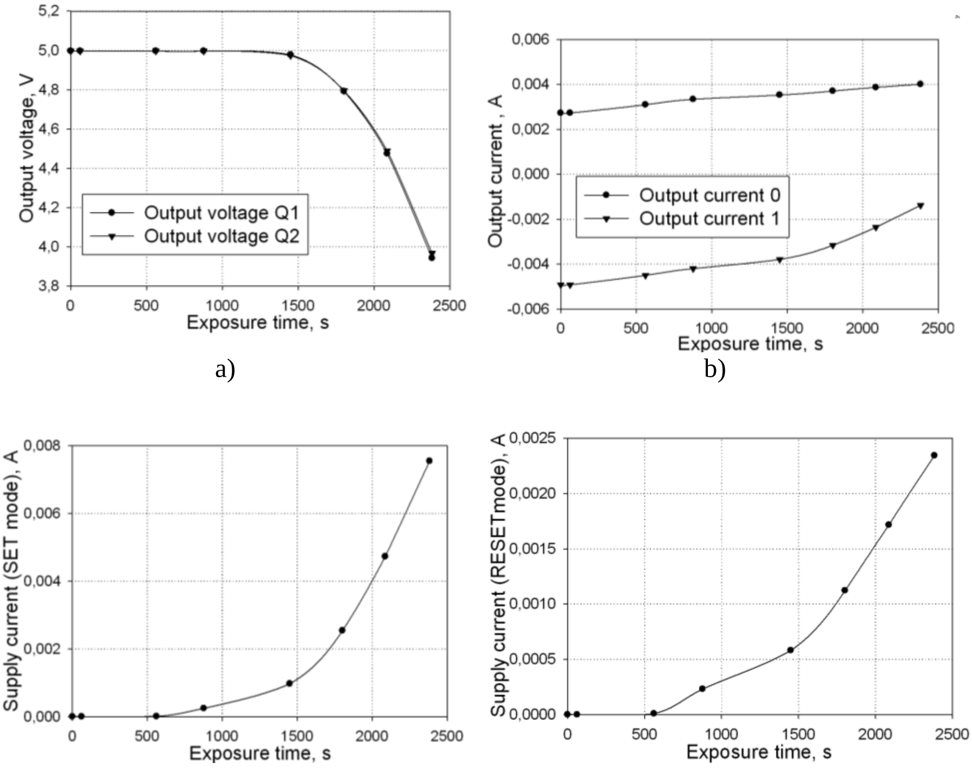
$$\Delta = (1+\Delta_\gamma)(1+\Delta_X) - 1 \approx \Delta_\gamma + \Delta_X \tag{6}$$

Dosimetric conformity of products is regulated by radiation test standards.

7. COMBINED TESTING EXAMPLE

For a test example, we have chosen a typical integrated circuit, HEF4013BT which is a dual CMOS D-trigger manufactured by NXP Semiconductors.

Let's estimate the calibration factor for HEF4013BT. As the sample was irradiated, we controlled its operation and measured acceptability criteria (U_{OH}, I_{OH}, I_{OL}, I_{CCH}, I_{CCL}) versus the level (time) of exposure (see Fig. 1).



a) b)

c) d)

Fig 1 Experimental dependences of selected HEF4013BT parameters versus exposure time: a) U_{OH}, b) I_{OH}, I_{OL}, c) I_{CCH}, d) I_{CCL}

Next, we have to assess applicability of the method. For this purpose, we expose the circuit in a gamma irradiation facility (sample 13) and in an X-ray irradiation facility (sample 6). Fig. 2 shows matching of dependencies of increment of supply current in the SET mode for these samples. The calibration transformation factor (1) was estimated by the least squares method. At k=0.0328, relationship (2) is valid even at $\delta = 0$ at least at three different exposure levels. Therefore, we can conclude that the combined test method is applicable to the particular sample.

Further, the two lots of integrated circuites are irradiated. The first lot (2 samples, including sample #13) is exposed in a gamma irradiation facility, while the second lot (5 samples, including #6) is exposed in an X-ray facility.

As a calibration parameter, the supply current in the SET state (I_{CCH}) is selected. Since the dependence of the parameter increment versus exposure level is monotonous, such dependence is not normalized.

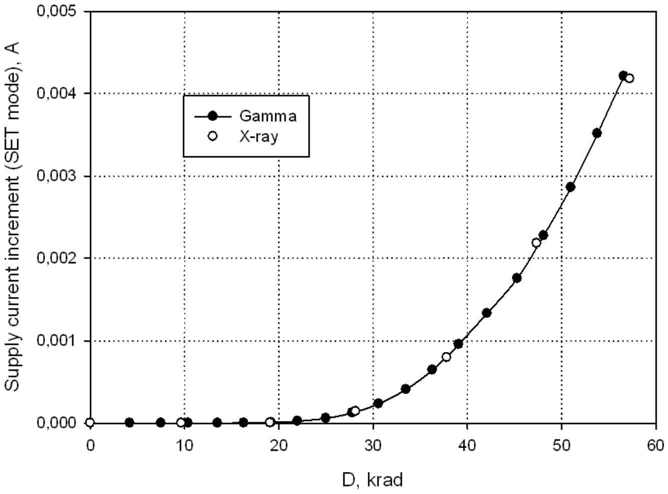


Fig. 2 Matching of dependencies of supply current in the SET mode at exposure of HEF4013BT in a gamma irradiation facility (sample 13) and an X-ray irradiation facility (sample 6) at *k* = 0.0328.

The calibration level of parameter $q_0 = 3$ mA is selected. For the *j*-th sample of lot 1, $j = 1...n_\gamma$, based on the experimental dependency $q_{\gamma j}(D_\gamma)$, the TID value $D_{\gamma j}$ is determined from the following condition (Fig. 1)

$$\left|\frac{q_{\gamma\, j}(D_{\gamma\, j})-q_0}{q_0}\right|<\delta$$

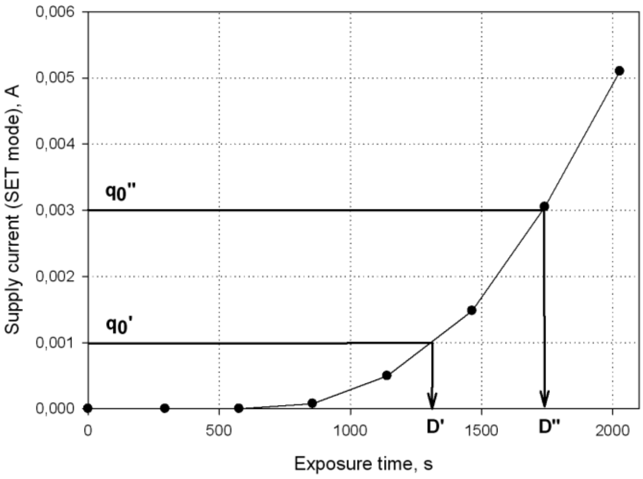


Fig. 3 Then, the levels of exposure D_i matching the q_0 criteria, are determined.

Resulting D_γ= {51.6, 44.6}. Similarly, the values of D_{Xi}, $i = 1...n_X$ are determined for lot 2: D_X = {1734, 1733, 1521, 1488, 1569}.

Then, the point estimate of calibration factor k is made:

$$\overline{D_X} = 1609, \quad \overline{D_\gamma} = 48.1, \quad k = \frac{\overline{D_\gamma}}{\overline{D_X}} = 0.0299.$$

The lower boundary k_L of the calibration factor confidence interval is calculated at P=0.95: $K=k_L=0.025$. A relative error of measuring X-ray exposure duration Δ_X for automatic source control is under 1%, therefore the dosimetry testing error is determined by the relative error of gamma irradiation dosimetry Δ_γ which is 15% according to the dosimetric system data sheet.

If the case for X-ray testing is proven, electronic components informative parameters immeasurable under the gamma irradiation conditions are measured on the X-ray source, otherwise the entire test is run the on the gamma irradiation facility.

8. CONCLUSION

The method of microelectronics TID hardness assurance testing based on a combination of gamma and X-ray irradiation facilities clarifies and develops the method of X-ray tests dosimetry specified in regulatory documents. This method can improve reliability of dosimetry of X-ray testing, fully combining, within a single test cycle, the capabilities and benefits, both of gamma irradiation facilities ensuring adequacy of test effects and of X-ray irradiation facilities, allowing to determine all informative parameters of electronic components (including precision and performance), and check all the operating modes and conditions directly under irradiation. The newly proposed method of combined electronic component testing offers the benefit of working with small sample lots and presents clear applicability criteria.

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