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Study of the Influence of the Voltage Regulator Integrated Circuit Topology on its Radiation Hardness

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Abstract

Method of recording responses to radiation exposure is considered using the X-ray complex RIK-0401 and it is shown that for linear voltage regulators integrated circuits it allows diagnosing presence of changes in their topology. Four types of integrated circuits (ICs) of IS-LS1-1.8V type have been studied. They are equivalent in their main electrical parameters, but have differences in the output key design (vertical transistors with different base wiring), current mirrors and differential stages. ICs have modified design of the output key base: 1) vertical *p-n-p*-structures (Type 1); 2) mixed (lateral+vertical) *p-n-p*-structures (Type 2); 3) design as in the foreign analogue and vertical *p-n-p*-structures (Type 3); 4) design as in the foreign analogue and mixed (lateral+vertical) *p-n-p*-structures (Type 4). It has been found that the highest radiation hardness to the total ionizing dose effects is demonstrated by samples of Type 1 and Type 2. RADON-23 laser complex (with a maximum energy density of 200 mJ/cm^2) has been used for examination of voltage regulator samples to impulse ionizing radiation hardness. The thyristor effect has not been fixed in all studied samples of Type 1–4. Results of the research allow developing methods for increasing the radiation hardness of the IS-LS1-1.8V by varying the topology of microcircuits and choosing the most advantageous option for manufacturing the output key.

Keywords: voltage regulator, total ionizing dose effects, ionizing radiation, radiation hardness

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Исследование влияния топологии интегральной микросхемы стабилизатора напряжения на его радиационную стойкость

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Рассмотрен метод регистрации отклика на радиационное воздействие с использованием рентгеновского комплекса РИК-0401 и показано, что для линейных стабилизаторов напряжения интегральных схем он позволяет диагностировать наличие изменений в их топологии. Исследованы 4 типа микросхем ИС-ЛС1-1.8В, которые по основным электрическим параметрам эквивалентны, но имеют отличия в исполнении выходного ключа (вертикальные транзисторы с различным разведением базы), токовых зеркал и дифференциальных каскадов: с измененным исполнением базы выходного ключа и вертикальными *p-n-p*-структурами (Тип 1); с измененным исполнением базы выходного ключа и смешанными (латеральные + вертикальные) *p-n-p*-структурами (Тип 2); с исполнением базы выходного ключа как у зарубежного аналога и вертикальными *p-n-p*-структурами (Тип 3); с исполнением базы выходного ключа как у зарубежного аналога и смешанными (латеральные + вертикальные) *p-n-p*-структурами (Тип 4). По результатам исследования установлено, что наибольшую радиационную стойкость к эффектам поглощённой дозы демонстрируют образцы микросхемы стабилизатора напряжения ИС-ЛС1-1.8В Типа 1 и Типа 2. Для исследования образцов линейного стабилизатора на стойкость к воздействию импульсного ионизирующего излучения использовался лазерный комплекс РАДОН-23 с максимальной плотностью энергии 200 мДж/см^2. Установлено отсутствие тиристорного эффекта в исследованных Типах 1–4 линейного стабилизатора напряжения ИС-ЛС1-1.8В. Полученные результаты позволяют разрабатывать способы повышения радиационной стойкости линейного стабилизатора напряжения ИС-ЛС1-1.8В путём варьирования топологии интегральных микросхем и выбирать наиболее выгодный вариант изготовления выходного ключа.

Ключевые слова: стабилизатор напряжения, эффекты поглощенной дозы, ионизирующее излучение, радиационная стойкость

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Introduction

It is known that the important element of modern microelectronics are integrated circuits (IC) of voltage regulators, since almost any electronic circuit (simple circuits on transistors, operational amplifiers, digital and microprocessor systems, etc.) requires one or more stable sources of direct current for its stable operation [1–4].

For functioning and development of critically important industries (space exploration, aircraft manufacturing, nuclear power engineering, etc.) it is necessary the operation of electronic components under radiation exposure, including linear voltage regulators [4].

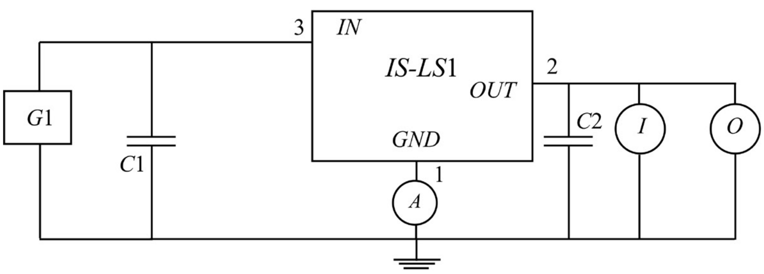
In particular, for discrete devices of the electronic component base and integrated circuits, the nature of their topology determines their radiation hardness [4–7]. Thus, it has been established that the topological features of bipolar transistor structures determine their main electrical characteristics (gain, current-voltage characteristics) for *n-p-n* and *p-n-p* transistors [4, 5], as well as bipolar analog integrated circuits of comparators and voltage regulators (consumption current, output voltage, etc.) under radiation exposure, in particular on the total ionizing dose value [4, 6, 7].

On account of this, the main goal of this investigation was to study the radiation hardness of linear voltage regulators produced on the basis of an imported analogue, equivalent in electrical parameters, but having topological differences (with different output key designs), which will optimize the choice of optimal topology options to increase the radiation hardness of voltage regulators integrated circuits.

Materials and methods

The object of the study was linear voltage regulator in the TO-220-3 package, with an output voltage of 1.8 V (hereinafter IS-LS1-1.8V), manufactured by JSC "GRUPPA KREMNY EL" [8]. The study was carried out using the developed hardware and software complex (HSC) consisting of the following: X-ray equipment RIK-0401 [9], X-ray comparator DRI-0401, a set of measuring equipment (sources-measuring instruments PXIe-4143, PXIe-4139), and the developed software. Previously, the HSC was successfully tested to study the radiation behavior [10] of the linear LDO positive voltage regulator IS-LS-9V (manufactured by JSC "GRUPPA KREMNY EL"). The schematic diagram of the developed HSC is described in detail in [10–11]. Additionally, for examination of voltage regulator samples to impulse ionizing radiation hardness the RADON-23 [9] laser complex (with a maximum energy density of 200 mJ/cm^2) also was used.

The X-ray equipment RIK-0401 is a RAP-100 X-ray source with a maximum anode voltage of 80 kV and a maximum anode current of 0.3 mA, installed in an X-ray protective chamber with a two-coordinate positioning system with a step of 0.1 mm. The intensity of X-ray radiation was controlled using a DRI-0401 X-ray comparator. The HSC was controlled using specialized software developed in the LabView program that allows measuring the controlled parameters at a specified time interval, and also provides the ability to set the electrical operating mode of the IC samples during irradiation process. For linear voltage regulator microcircuits, the HSC allows monitoring the output voltage, minimum voltage drop, consumption current, voltage instability, and current instability. The linear voltage regulator samples were installed on the contact device board in accordance with the diagram shown in Figure 1*a*. To ensure free access of X-ray radiation to the linear voltage regulator crystal, decapsulation was performed for the samples under study (see Figure 1*b*).



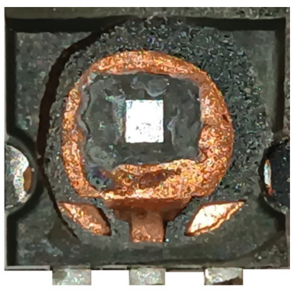


Figure 1 – Scheme of set-up for switching on the voltage regulators microcircuit during radiation exposure studies (*a*): *G*1 – PXIe-4143 power supply, *I* – electronic load (PXIe-4139), *O* – voltmeter (a built-in PXIe-4139 meter is used), *C*1 =1 µF, *C*2 = 10 µF; the decapsulated IS-LS1-1.8V sample (*b*)

Results and discussion

During the radiation experiments were studied four types of IS-LS1-1.8V, which are equivalent in their main electrical parameters, but have differences in the design of the output key (vertical transistors with different base wiring), current mirrors and differential stages: Type 1 with a modified design of the output key base and vertical *p-n-p*-structures; Type 2 with a modified design of the output key base and mixed (lateral + vertical) *p-n-p*-structures; Type 3 with the design of the output key base as in the foreign analogue and vertical *p-n-p*-structures; Type 4 with the design of the output key base as in the foreign analogue and mixed (lateral + vertical) *p-n-p*-structures. For comparison, the analog of IS-LS1-1.8V the voltage regulator LT1963 [12] was also examined.

According to the results of studies it was established that the most sensitive parameters of linear voltage regulator's to the total ionizing dose effects are the output voltage and the consumption current. Figure 2 shows the dependence of the output voltage on the total ionizing dose value for all samples of the IS-LS1-1.8V and the analog of the LT1963 voltage regulator.

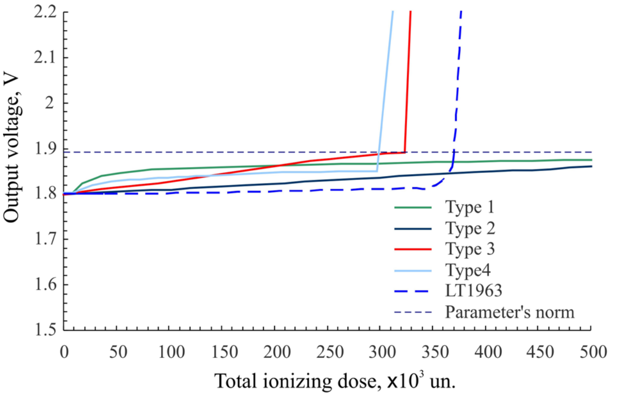


Figure 2 – Dependence of change of the output voltage for the integrated circuit IS-LS1-1.8V and LT1963 analogue on the value of the total ionizing dose (the dotted line is the norm of the parameter of the output voltage of the microcircuit)

For the Type 1 microcircuit sample, the output voltage gradually increases from 1.8 to 1.87 V at an total ionizing dose of 500×10^3 un., without reaching the limit of the parameter's norm (1.89 V for the IS-LS1-1.8V microcircuit). For the Type 2 sample, the output voltage gradually increases from 1.8 to 1.85 V at an total ionizing dose of 500×10^3 un., also without reaching the limit of the parameter norm. For the Type 3 and Type 4 samples, the output voltage gradually increases and reaches the limit of the parameter norm at an total ionizing dose of 324×10^3 and 300×10^3 un., respectively. Further, with an increase in the total ionizing dose, a functional failure of the Type 3 and Type 4 microcircuit samples is fixed. For the LT1963 analogue, similar behavior is recorded with the parameter norm being reached at an total ionizing dose of 370×10^3 un. and subsequent functional failure with an increase in the total ionizing dose.

Thus, the highest radiation hardness in terms of output voltage to the total ionizing dose effects is demonstrated by microcircuits with the Type 1 topology (with a modified design of the output key base and vertical *p-n-p*-structures) and Type 2 (with a modified design of the output key base and mixed (lateral+vertical) *p-n-p*-structures), superior, including foreign analog of LT1963.

Further, Figure 3 shows the dependence of the consumption current on the total ionizing dose value for all samples of the IS-LS1-1.8V and the LT1963 analog.

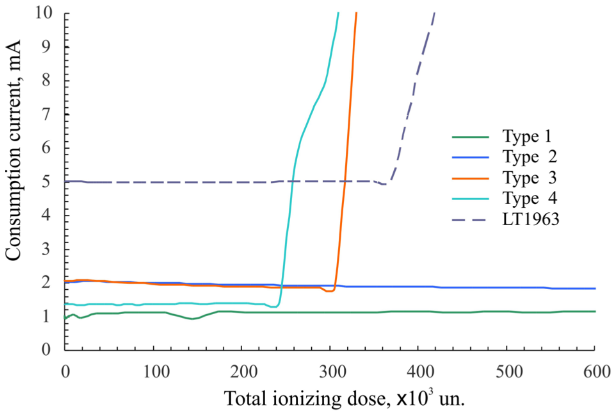


Figure 3 – Dependence of change of the consumption current for the integrated circuit IS-LS1-1.8V and LT1963 analogue on the value of the total ionizing dose

For the Type 1 microcircuit sample, the consumption current value changes insignificantly from 1.03 to 1.87 mA with an increase in the final total ionizing value to 600×10^3 un. For the Type 2 microcircuit, the consumption current value also changes insignificantly from 2.07 to 1.97 mA with an increase in the total ionizing dose up to 600×10^3 un. For the Type 3 sample, the consumption current value also changes insignificantly (2.07 to 1.85 mA) up to an total ionizing dose value of 305×10^3 un. and then

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begins to increase sharply, reaching a value of 10 mA at a dose of 330×10^3 un. Analogously, for the Type 4 sample, the current consumption value changes slightly (1.35 to 1.39 mA) up to the total ionizing dose of 243×10^3 un. and then begins to increase sharply, reaching a value of 10 mA at a dose of 310×10^3 un.

As follows from Figure 3, for the LT1963 analog, the current consumption value practically does not change (≈4.99 mA) up to the total ionizing dose of 369×10^3 un. and then begins to increase harshly, reaching a value of 10 mA at a dose of 428×10^3 un.

Thus, the maximum stability and the lowest current consumption value under radiation conditions are demonstrated by voltage regulator IC samples with Type 1 and Type 2 topology, being the most radiation hardness in this range of ionizing radiation dose.

In addition, the IS-LS1-1.8V samples have been testing on hardness to pulsed ionizing radiation using the RADON-23 laser complex with a maximum energy density of up to 200 mJ/cm^2. The RADON-23 laser complex operating mode is following: the wavelength – 1064 nm; the radiation pulse energy – 120 mJ; the effective pulse duration – 10 ns; the beam diameter – 11 mm. It was found that the thyristor effect is not observed in the studied samples of Type 1–4 both at a minimum energy density of 1 mJ/cm^2 (see Figure 4*a*) and at a maximum of 200 mJ/cm^2 (see Figure 4*b*). The interruption time of the IS-LS1-1.8V operation was 300 µs (energy density – 1 mJ/cm^2) and 700 µs (energy density – 200 mJ/cm^2) correspondingly, which does not exceed the required standard.

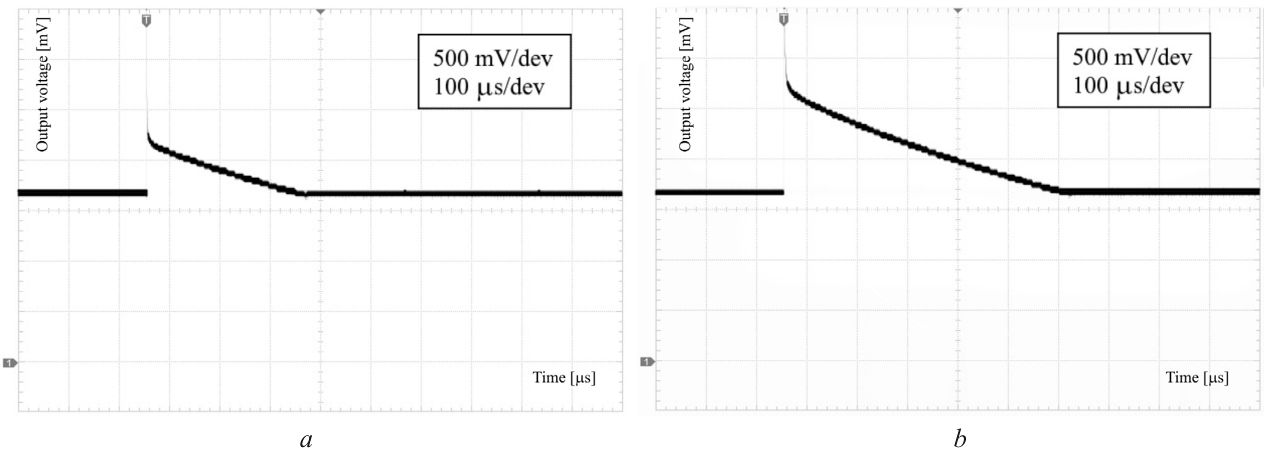

Figure 4 – The oscillogram of the IS-LS1-1.8V integrated circuit sample under the exposure of pulsed ionizing radiation (RADON-23 laser complex) at voltage supply of 20 V and load current of 25 mA with energy density (scale factor – 500 mV/dev, 100 µs/dev): *a* – 1 mJ/cm^2; *b* – 200 mJ/cm^2

Thus, the method used to study the response to radiation exposure made it possible to diagnose significant differences in the radiation hardness of voltage regulator microcircuits depending on the presence of changes in their topology, despite the equivalence of the electrical parameters of the types studied. Therefore, this method is perspective and can be used for the design and development of electronic component base products operating under radiation conditions [3, 6, 13–15].

Conclusion

Influence of the integrated circuit topology of the IS-LS1-1.8V linear voltage regulator on its radiation hardness has been studied. It was found that the maximum of radiation hardness to the total ionizing dose effects (by parameters of output voltage and consumption current) is demonstrated by voltage regulator microcircuits with the topology of Type 1 (with a modified design of the output key base and vertical *p-n-p*-structures) and Type 2 (with a modified design of the output key base and mixed (lateral+vertical) *p-n-p*-structures), surpassing the other two types and its foreign analogue LT1963. Study of IS-LS1-1.8V samples of Type 1–4 for hardness to pulsed ionizing radiation showed that the thyristor effect was not fixed in the investigated samples up to an energy density of 200 mJ/cm^2.

Results obtained allow to formulate methods for increasing the radiation resistance of the linear voltage regulator IS-LS1-1.8V and to choose the most advantageous option for manufacturing the output key. The method proposed can be also adapted in monitoring and assessing the trusted electronics and radiation hardness at all stages of the life cycle of electronic component base products (during development, production, etc.).

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