PHYSICAL ELECTRONICS

Conference materials
UDC 537.312.54; 621.382.33
DOI: https://doi.org/10.18721/JPM.183.229

Radiation hardness of *n–p–n* type bipolar transistor for voltage regulators

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Abstract. The characteristics (collector current, base current, common-emitter current gain) of *n–p–n* type bipolar transistor for voltage regulator depending on total ionizing dose radiation using projected X-ray research complex were established. The functional dependencies and model of common-emitter current gain depending on total ionizing dose have been obtained.

Keywords: *n–p–n* type bipolar transistor, ionizing dose effects, X-ray irradiation.

Funding: This study was supported by the Russian Ministry of Science and High Education (agreement with the Russian Ministry of Science and High Education of 9 February 2023 No. 075-11-2023-008) using state support measures provided by the Russian Federation Government's Decree of 9 April, 2010 No. 218.

Citation: Rybalka S.B., Sitnikov Yu.A., Kulchenkov E.A., Demidov A.A., Radiation hardness of *n–p–n* type bipolar transistor for voltage regulators, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.2) (2025) 149–154. DOI: https://doi.org/10.18721/JPM.183.229

Материалы конференции
УДК 621.382.2/.3; 537.312.54
DOI: https://doi.org/10.18721/JPM.183.229

Радиационная стойкость биполярного транзистора *n–p–n* типа для стабилизаторов напряжения

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Аннотация. Для биполярного транзистора *n–p–n* типа для стабилизатора напряжения были установлены характеристики (ток коллектора, ток базы, коэффициент усиления по току) в зависимости от суммарной поглощенной дозы ионизирующего излучения с использованием спроектированного рентгеновского исследовательского комплекса. Получены функциональные зависимости и модель коэффициента усиления по току в зависимости от суммарной поглощенной дозы.

Ключевые слова: биполярный транзистор *n–p–n* типа, эффекты поглощенной дозы, рентгеновское излучение

Финансирование: Работа выполнена при финансовой поддержке Министерства науки и высшего образования РФ (соглашение с Министерством науки и высшего образования от 9 февраля 2023 г. № 075-11-2023-008) с использованием мер государственной поддержки, предусмотренных постановлением Правительства РФ от 9 апреля 2010 г. № 218.

Ссылка при цитировании: Рыбалка С.Б., Ситников Ю.А., Кульченков Е.А., Демидов А.А. Радиационная стойкость биполярного транзистора *n–p–n* типа для стабилизаторов напряжения // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 149–154. DOI: https://doi.org/10.18721/JPM.183.229

Introduction

Study of the radiation hardness of voltage regulators to the total ionizing radiation dose effects is important goal for electronics [1]. It was earlier was established [2] that there is possibility to increase radiation hardness of voltage regulator IS-LS3-5V based on compensating method that using *n–p–n* type bipolar transistor included as additional element in its scheme. Therefore, study of *n–p–n* type bipolar transistor radiation-sensitive characteristics and establishment its radiation hardness to the total ionizing dose effects during ionizing radiation using X-ray research complex is important scientific task. Thus, solving this task will make it possible to increase the radiation hardness of voltage regulator integrated circuit with this transistor using above-mentioned compensating method and, as a result, the electronic devices of spacecraft equipment developed on this transistor could be stably operated under ionizing radiation conditions in space.

Materials and methods

The *n–p–n* type bipolar transistor was designed by Bryansk State Technical University and then produced by JSC "GRUPPA KREMNY EL" by BiCMOS (Bipolar Complementary Metal Oxide Semiconductor) technology as element of some linear positive voltage regulator [2]. Investigation of *n–p–n* type bipolar transistor characteristics during ionizing radiation has been carried out using the earlier developed X-ray research complex (XRC) described in [3]. In particular, the characteristics study of *n–p–n* type bipolar transistor under radiation conditions was performed at following operating mode of XRC: anode voltage of 70 kV, anode current of 150 μA, the rate of radiation dose accumulation was 150 un./s (units of the DRI-0401 comparator including in X-ray research complex), distance between the X-ray tube window and the sample of 25 mm.

Results and discussion

The *n–p–n* type bipolar transistor was connected according to the typical scheme for measuring of the collector current, base current and common-emitter gain. Transistor was operated under radiation in next electrical mode: the collector-emitter voltage V_{CE} is 16 V (measured by Fluke 8845A multimeter) and two base currents I_B values of 100 nA and 1 μA (measured by Keithley 6485 picoamperemeter).

Fig. 1 shows the collector current I_C, base current I_B and common-emitter current gain β depending on total ionizing dose D for investigated *n–p–n* type bipolar transistor. The value of collector current decrease with increasing of total ionizing dose for both base currents I_B (100 nA and 1 μA). The current I_B (initial base current values: 100 nA and 1 μA) lightly increases as total ionizing dose increase. The current gain β for transistor at I_B = 100 nA (collector-emitter voltage is 16 V) at first increases from 71, then reach the maximal value of 101 at dose of 24×10^3 un. and further decreases up to 9 at final total ionizing dose D = 800×103 un. In case when the base current is 1 μA (common-emitter voltage is 16 V) the β decreases from 116 up to 14 at $D = 800\times10^3$ un. It should be noted that established here current gain dependence β on total ionizing dose D depends on base currents I_B values for *n–p–n* analogous type bipolar transistor that was obtained during its irradiation by γ-ray radiation [4]. In addition, the same nonlinear dependence of current gain on total ionizing dose with extremum take places [4]. For engineers and developers of voltage regulators, that included same *n–p–n* type bipolar transistor, that operating under radiation conditions it is important to know the analytical dependence of common-emitter current gain β its transistor from radiation dose for calculation of addition resistance of compensation resistor in the feedback circuit for preventing of output voltage changing [2].

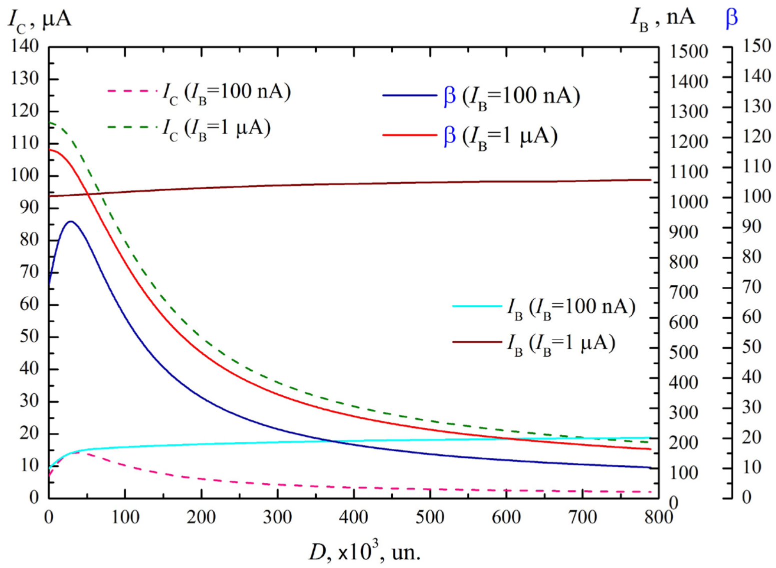

Fig. 1. Collector current I_C, base current I_B and common-emitter current gain β dependences on total ionizing dose D for *n–p–n* type bipolar transistor (collector-emitter voltage V_{CE}=16 V)

Therefore, the analytical expressions have been obtained to assist design engineers based on regression analyses methods, especially, the analytical dependencies of the common-emitter gain β(D) on the total ionizing dose D for *n–p–n* bipolar transistor for two different base currents I_B (I_B = 100 nA (Eq. 1) and I_B = 1 µA (Eq. 2), V_{CE}=16 V) are following form:

$$\beta(D) = -1.982 \cdot 10^{-7} \cdot D^3 + 4.278 \times 10^{-4} \cdot D^2 - 30.5 \cdot 10^{-2} \cdot D + 83.463, \quad (1)$$

$$\beta(D) = -3.101 \cdot 10^{-7} \cdot D^3 + 6.427 \cdot 10^{-4} \cdot D^2 - 43.8 \cdot 10^{-2} \cdot D + 117.075, \quad (2)$$

where β is the common-emitter current gain, D is the total ionizing dose (10^3 un.).

In modern engineering calculations of integrated circuits use special electronic circuit simulators widely known as SPICE (Simulation Program with Integrated Circuit Emphasis) programs (PSPICE, OrCAD, LTspice, Micro-Cap etc.) that are based on physico-mathematical models of electronic devices [5]. Further, for developing of a linear voltage regulator integrated circuit where included this *n–p–n* type bipolar transistors during ionizing radiation it is necessary have its SPICE-model [4]. As the basic for SPICE-model of *n–p–n* bipolar transistor was chosen the Ebers-Moll model [5]. In Fig. 2, *a* is shown the developed scheme of SPICE-model in LTspice program [5] for *n–p–n* type bipolar transistor operating under ionizing radiation which presented in SPICE subcircuit format text that included the following elements: base resistance (RB), collector resistance (RC), emitter resistance (RE), additional resistances (R3), arbitrary behavioral base current source (IBr), arbitrary behavioral collector current source (ICr), base node (B), collector node (C), emitter node (E). The function for base current source (IBr in Fig. 2, *a*) functionally dependent on irradiation time obtained on the basis of Ebers-Moll model is following form:

$$I = (1-a_f) I_{es} e^{\frac{V(B,E)}{V_t} - 1} + (1-a_r) I_{cs} e^{\frac{V(B,C)}{V_t} - 1} - 4.821 \cdot 10^{-15} t^2 + 2.661 \cdot 10^{-11} t, \quad (3)$$

where t is the irradiation time (s), $V(B,E)$ is the voltage difference between node B and E in Fig. 2, *a* (V), $V(B,C)$ is the voltage difference between node B and C in Fig. 2, *a* (V), $a_f = 9.92 \cdot 10^{-1}$ is the the forward current gain of the common-base configuration, I_{es}=$7.26 \cdot 10^{-15}$ is base-emitter saturation current (A), $a_r = 6.30 \cdot 10^{-1}$ is the reverse current gain of a common-base configuration, $I_{cs} = 1.14 \cdot 10^{-15}$ is the base-collector saturation current (A), $V_t = 25.9 \cdot 10^{-3}$ is the thermal voltage.

Similarly, the function for collector current source (ICr in Fig. 2, *a*) functionally dependent on irradiation time is next:

$$I = a_f I_{es} e^{\frac{V(B,E)}{V_t}-1} - I_{cs} e^{\frac{V(B,C)}{V_t}-1} - 1.09\cdot 10^{-15} t^3 + 1.499\cdot 10^{-11} t^2 - 6.744\cdot 10^{-8} t, \tag{4}$$

where t is the irradiation time (s), $V(B,E)$ is the voltage difference between node B and E in Fig. 2, *a* (V), $V(B,C)$ is the voltage difference between node B and C in Fig. 2, *a* (V), $a_f = 9.92\cdot 10^{-1}$ is the forward current gain of the common-base configuration, $I_{es}=7.26\cdot 10^{-15}$ is base-emitter saturation current (A), $I_{cs} = 1.14\cdot 10^{-14}$ is the base-collector saturation current (A), $V_t = 25.9\cdot 10^{-3}$ is the thermal voltage. Then the equations (3) and (4) described above were implemented in LTspice as SPICE subcircuit text (see Fig. 2, *a*) in accordance with LTspice command syntax using SPICE directive ".SUBCKT" [7]. In addition, the component's nominals, parameters and functions for functionally dependent base (IBr) and collector (ICr) current sources are indicated in the circuit text in Fig. 2, *a* (in particular, all parameters were included into subcircuit using the special [7] SPICE directive ".param" (see Fig. 2, *a*) for correct calculation in LTspice program using SPICE command syntax in the following form: forward current gain is 9.92e-1, base-emitter saturation current is 7.26e-15, reverse current gain is 6.30e-1, base-collector saturation current is 1.14e-14, thermal voltage is 25.9e-3). Then for developed SPICE-model in LTspice was create new symbol that define in Fig. 2, *b* as BJT. The developed SPICE-model for *n–p–n* type bipolar transistor then was connected as subcircuit in LTspice program (see Fig. 2, *b*) in accordance with common-emitter configuration (base current I_B = 1 μA and collector-emitter voltage V_{CE}=16 V) for its verification under ionizing radiation operating.

a)

```
* ------ BJT-RAD radiation model subcircuit -------
        * connections:          collector
        *                        |  base
        *                        |  |  emitter
        *                        |  |  |
        .SUBCKT   BJT            C  B  E
.param af=9.92e-1   Ies=7.26e-15   ar=6.30e-1   Ics=1.14e-14   Vt=25.9e-3
RB N001 B 15.05µ
RC C N002 5k
RE N003 N004 7k
* The equation for functionally dependent base current sources IBr:
B§IBr N001 N003 I=(1-af)*Ies*(exp(V(B,E)/Vt)-1)+(1-ar)*Ics*(exp(V(B,C)/Vt)-1)-4.821*10**-15*time**2+2.661*10**-11*time
* The equation for functionally dependent collector current sources ICr:
B§ICr N002 N003 I=af*Ies*(exp(V(B,E)/Vt)-1)-Ics*(exp(V(B,C)/Vt)-1)-1.09*10**-15*time**3+1.499*10**-11*time**2-6.774*10**-8*time
R3 N004 E 1
.end BJT
```

b)

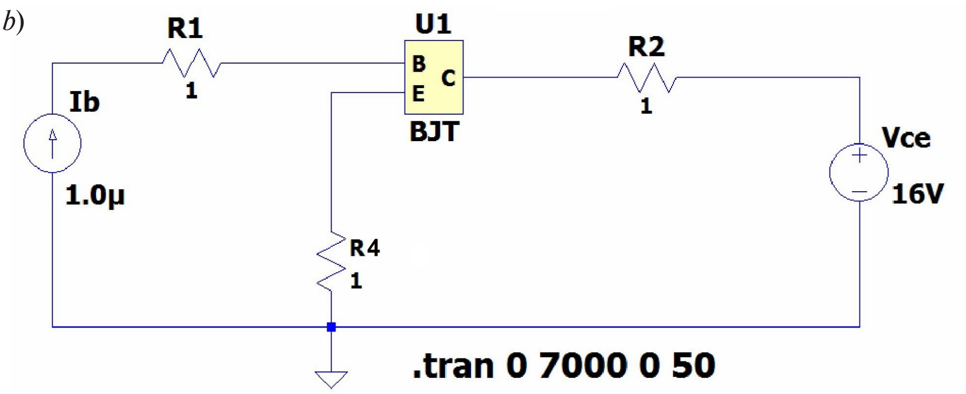

Fig. 2. Developed SPICE-model for *n–p–n* type bipolar transistor presented as SPICE subcircuit text (*a*); scheme in LTspice program for calculation of transistor's current gain dependence on ionizing radiation time for developed SPICE-model (BJT component, where B is base node, C is collector node, E is emitter node) at base current I_b = 1 μA and collector-emitter voltage V_{CE} = 16 V

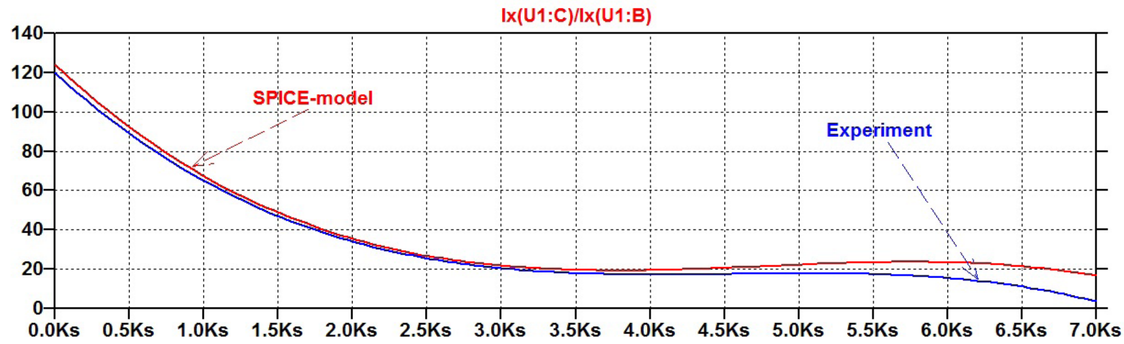

Fig. 3. Common-emitter current gain dependence on irradiation time (s) for *n–p–n* type bipolar transistor (base current is 1 μA, collector-emitter voltage is 16 V) calculated by model in LTspice

Fig. 3 shows calculation in LTspice program [6] by above SPICE-model in transient analysis mode for common-emitter gain (Ix(U1:C)/Ix(U1:B) = β) dependence on irradiation time (I_B = 1 μA, V_{CE} = 16 V) for *n–p–n* transistor. It can be seen that the calculated by SPICE-model and experimental dependencies are quite well comparable.

Thus, the proposed radiation dependent SPICE-model for the *n–p–n* bipolar transistor on the basis of the Ebers–Moll model give us possibility to perform in SPICE programs calculations of voltage regulator with this transistor included as additional element in its scheme for increasing its radiation hardness using compensating method described in [2].

Conclusion

The radiation hardness for *n–p–n* type bipolar transistor was studied using X-ray research complex. The dependencies of collector current, base current and common-emitter current gain from total ionizing dose radiation have been obtained. Because of this, for common-emitter current gain transistor's were established analytical dependencies on total ionizing dose and proposed SPICE-model necessary for improvement voltage regulator's scheme functioning under radiation conditions.

Acknowledgments

The results of the Research and Development have been achieved during the implementation of the project "Integrated microcircuits of analog signal converters in metal-polymeric package of various types: development and mastering of technology, replacement of imported analogs and organization of serial production' (agreement with the Russian Ministry of Science and High Education of 9 February 2023 No. 075-11-2023-008) using state support measures provided by the Russian Federation Government's Decree of 9 April, 2010 No. 218.

REFERENCES

1. **Gaul S.J., Vonno N., Voldman S.H., Morris W.H.**, Integrated Circuit Design for Radiation Environments, Wiley & Sons, Chichester. (2020).
2. **Pilipenko K.S., Kulchenkov E.A., Rybalka S.B., Demidov A.A.,** Method for increasing of the voltage regulator radiation hardness, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 3.1 (17) (2024) 191–194.
3. **Rybalka S.B., Demidov A.A., Kulchenkov E.A., Pilipenko K.S.,** Radiation behaviour study of linear voltage regulator, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 3.1 (17) (2024) 195–198.
4. **Belous A.I., Solodukha V.A., Shvedov S.V.,** Space Electronics, Tekhnosphera, Moscow. (2015).
5. **Sedra A.S., Smith K.C., Carusone T.C., Gaudet V.,** Microelectronic Circuits, Oxford University Press, Oxford/New York. (2020).
6. LTspice Simulator | Analog Devices. URL: https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html. Accessed August. 30, 2025.
7. **Farzin Asadi,** Essential Circuit Analysis Using LTspice®, Springer International Publishing AG, Cham. (2023).

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Received 08.08.2025. Approved after reviewing 31.10.2025. Accepted 31.10.2025.