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The Effect of Gamma Rays on the Main Static Characteristics of SiGe Transistors

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The article considers the effect of ^{60}Co gamma rays on the characteristics (the major ones for the analog ICs) of SiGe n-p-n transistors of SGB25V technology: the voltage across the forward-biased base-emitter junction, the dependence of the static base current gain (β) in the common-emitter configuration on emitter current, the output characteristic in the common-emitter configuration.

Key words: radiation hardness, SiGe-transistors, analog microcircuits, gamma rays, main static characteristics of transistor

Introduction

It is known that the sensors of spacecraft are often located outside the heated blocks, protected against the penetrating radiation (PR). Therefore, they are subjected to simultaneous exposure to low temperatures and PR. To improve the signal-to-noise ratio of these sensors it is reasonable to place an interface device closely to them, which realizes the sensor signal preprocessing and conveys information to the impenetrable block across the wire for final processing.

This interface is most often an analog IC, which should remain operative while simultaneously exposing to low temperatures and PR.

In some cases it is reasonable to apply the precision analog interfaces, implemented on bipolar transistors (BTs) for sensor signal processing.

Our studies [1], supplementing the works [2–4], have shown that SiGe BTs manufactured using IHP's SGB25V technology are appropriate for designing high-quality low-temperature analog ICs.

In the literature, the high radiation hardness of SiGe BTs [5–8] to the effect of gamma quanta [9–12], protons [13–15], including at low temperatures [16], as well as to the simultaneous influence of different types of radiation [17–20] has been noted many times. However, most papers considered the radiation-induced alteration of the Gummel's plots (the dependences of the collector current I_c and the base current I_b on the voltage across the forward-biased base-emitter junction U_{be}), and also the dependence of the gain $\beta = f(I_e)$

The aim of this article is to consider ^{60}Co gamma ray effect on SiGe BT characteristics, which determine the static parameters of the analog ICs (operational amplifiers (OA), voltage regulators, etc.).

1 The Samples under Investigation, the Instrument and the Experimental Technique

The test chip SGB25V_016P, consisting of two n-p-n-transistors of n-p-n H type connected in parallel, was studied. Each transistor contained 16 emitters with dimensions of 0.42x3.36 μm^2, arranged in the form of 8x2 matrix. The test chip was produced using the technology of 0.25 μm SiGe BiCMOS of SGB25V type and assembled into the package 5140.8-AH3 with the capacity of current-carrying elements not higher than 0.3 pF. The standard structure of the transistor is shown in Fig. 1, and its main parameters are presented in Table 1 [21].

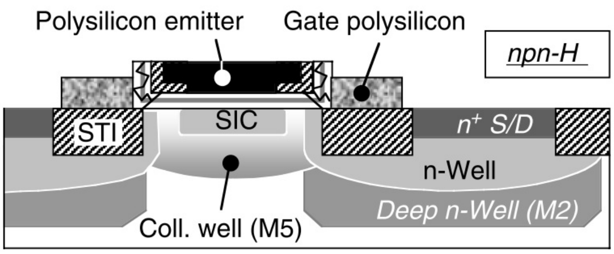

Fig. 1. The standard structure of n-p-nH transistor on IHP's SGB25V technology [21].

Table 1 The main parameters of n-p-nH transistor

Name of parameter	Value
Size of emitter	0.42x0.84 μm^2
Peak cut-off frequency	25 GHz
Collector-to-emitter breakdown voltage	7.0 V
Collector-to-base breakdown voltage	> 20 V
Early's voltage	> 100 V

The measurements were conducted by IPPP-1 tool [22]. Besides, special attention was given to the connecting circuit of the measured transistors in order to exclude self-excitation [1].

The irradiation of the samples with ^{60}Co gamma-quanta was carried out with gamma dose rate of 12.4 rad/s. After the irradiation sessions the total absorbed dose (D_{G}) was the following: 0.05; 0.1; 0.2; 0.5; 1.1; 2.1 Mrad. The irradiation of the samples with the short-circuited pins was conducted at the temperature of about 300 K. The measurements were carried out immediately after the irradiation. The duration of the measurement parameters did not exceed 1 hour.

2 The Measurement Results

A preliminary study of the storage time effect of one of BT samples on β value was made after the irradiation at room temperature (anneal time).

It was established that the worst case is the measurement of BT parameters immediately after the exposure of gamma rays (Fig. 2).

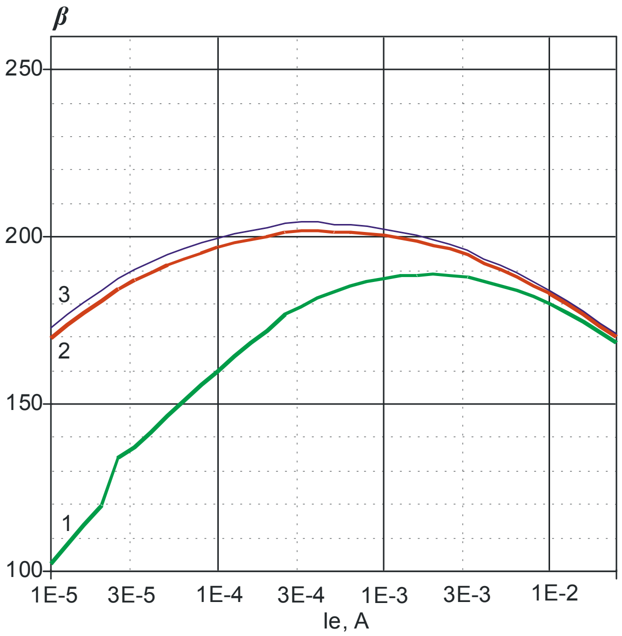

Fig. 2. The dependence of $\beta = f(I_e)$ when the collector-to-base voltage $U_{cb} = 1$ V and the absorbed dose $D_{\mathrm{G}} = 2.1$ Mrad for the various anneal time: 1 — without anneal, 2 - 4 hours, 3 - 72 hours.

It was in this mode (without anneal) that four BT samples were measured, which showed close results (Fig. 3).

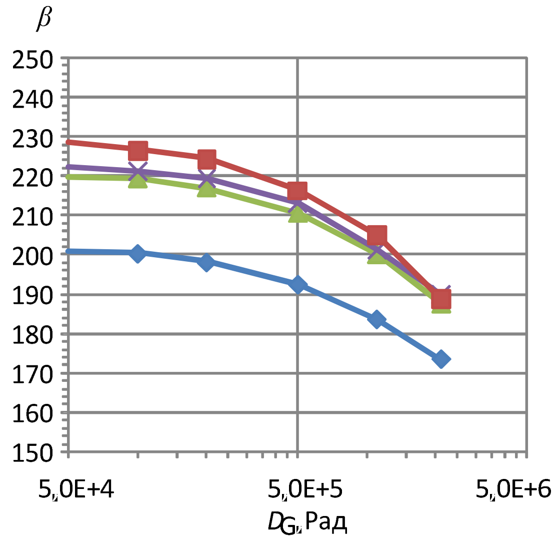

Fig. 3. The dependence of β on D_{G} absorbed dose for four BT samples, when $U_{cb} = 1$ V, $I_e = 1$ mA.

The graphs of changes of β gain at various doses of gamma rays for BT sample No.3 with the dependence $\beta = f(I_e)$, which was the closest to the average (Fig. 3), are given in Fig. 4.

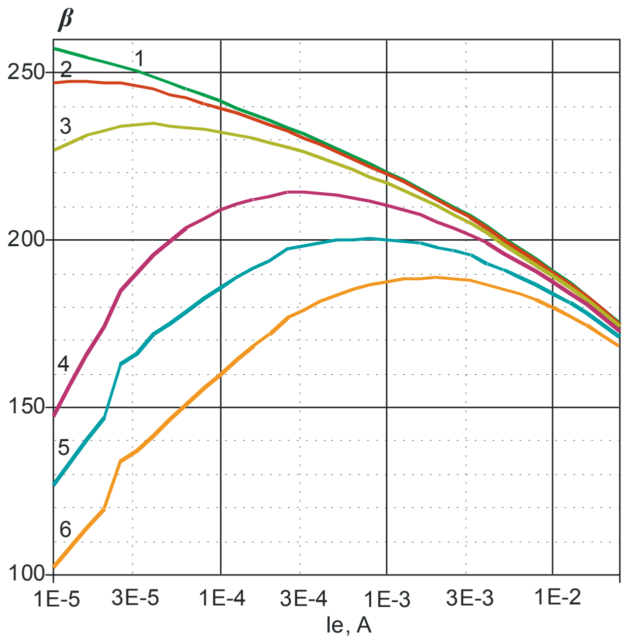

Fig. 4. The dependence of $\beta = f(I_e)$, when $U_{cb} = 1$ V (without anneal): 1 — before the irradiation; 2 – if $D_{\mathrm{G}} = 50$ Krad, 3 — $D_{\mathrm{G}} = 200$ Krad, 4 — $D_{\mathrm{G}} = 500$ Krad, 5 — $D_{\mathrm{G}} = 1.1$ Mrad, 6 — $D_{\mathrm{G}} = 2{,}1$ Mrad.

The output characteristic of BTs in the common-emiter configuration at various D_{G} is shown in Fig. 5. This dependence enables to determine the changes of the output differential resistance of the transistor

(R_{out}) and its Early's voltage (U_A)

$$R_{\text{out}} = \frac{\Delta U_{ce}}{\Delta I_c} \approx \frac{U_{\text{A}}}{I_c}. \quad (1)$$

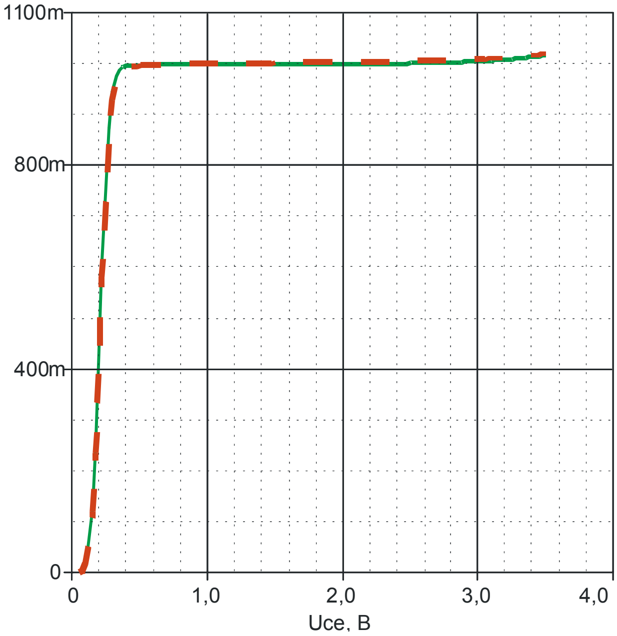

Fig. 5. The normalized dependence of I_c on the collector-to-emitter voltage U_{ce} at I_b=8 μA: the block curve – $I_c/1.715$ mA, when $D_{\text{G}} = 0$; the broken curve – $I_c/1.508$ mA, when $D_{\text{G}} = 2.1$ Mrad.

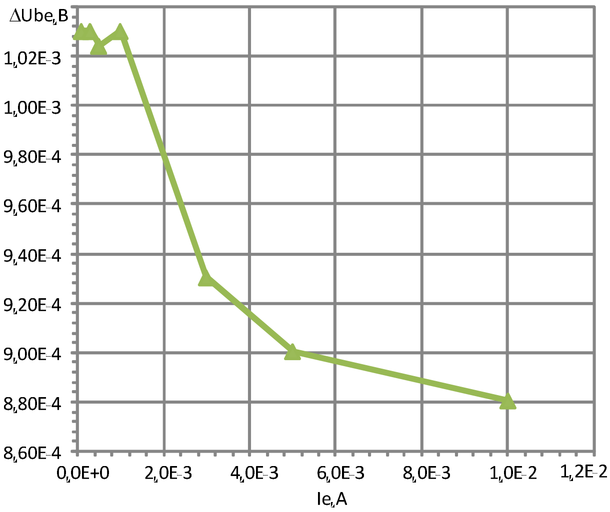

Fig. 6. The effect of the absorbed dose D_{G}=2.1 Mrad on the changes of the emitter-to-base voltage of BTs relating to the normal conditions (D_{G}=0) at various emitter currents (I_e).

The dependence of changes of the emitter-to-base voltage of BTs on the absorbed dose of gamma-quanta D_{G}=2.1 Mrad is shown in Fig. 6.

The analysis of the obtained results enabled us to establish the following features of characteristics of SiGe n-p-n-transistors of SGB25V technology:

1. When $D_{\text{G}} = 2.1$ Mrad, gamma rays practically don't affect U_{be} value at I_e = Const. Thus, when $I_e = 100$ μA, U_{be} decreased (in comparison with the normal conditions) by 1.03 mV; when I_e = 1 mA — by 0. 95 mV; when I_e = 10 mA — by 0.88 mV. On this basis we can assume that the parameters of the analog ICs, determined by U_{be} value (the offset voltage of OA, the coordinates of the steady-state behavior, etc), will be low-sensitive to the effect of gamma rays.

2. Gamma rays strongly affect β value only in the area of small emitter currents. Therefore, providing the operating mode of BTs with the heavy density of the emitter current, it is possible to reduce the radiation-induced alteration of β and, thus, the effect of gamma rays on such parameters as the input resistance of the emitter followers, the transfer ratio of the "current mirrors", etc.

3. Usually, to increase the voltage gain in the analog ICs the active loads (ALs) are used on the transistors with a high value of the output small-signal resistance. It follows from Fig. 5, gamma rays have little effect on output characteristic of BT in the common-emitter configuration. Consequently, the voltage gain of stages with AL will practically not change when exposure to gamma rays.

3 The Methods of Decreasing the Effect of β Degradation of Transistors on the Main Parameters of the Differential Amplifiers

To decrease the effect of gamma rays on the steady-state behavior of the analog ICs, for example, for the zero level of the OA with one high-impedance node, it is reasonable to apply the special circuit techniques, developed in [23, 24].

If we assume that all the n-p-n and p-n-p transistors of OA of Fig. 7, containing identical input differential stages (DS1, DS2), current mirror (CM1) and buffer amplifier (BA1), operate at the same emitter current, equal to some quantum I_0, then the errors of the output current coordinates of each functional node of OA (their differences from the ideal value of I_0) can be described by the following combined equation

$$\begin{aligned} I_{1.1} &= I_0 + A_{p1.1} I_{bp} + A_{n1.1} I_{bn}, \\ I_{2.1} &= I_0 + A_{p2.1} I_{bp} + A_{n2.1} I_{bn}, \\ I_{1.2} &= I_0 + A_{p1.2} I_{bp} + A_{n1.2} I_{bn}, \\ I_{2.2} &= I_0 + A_{p2.2} I_{bp} + A_{n2.2} I_{bn}, \end{aligned} \quad (2)$$

$$I_{CM2} = I_{1.1} + I_{1.2} + \xi_{p1} I_{bp} + \xi_{n1} I_{bn} \quad (3)$$

where I_{bp}, I_{bn} — base currents of the n-p-n and p-n-p transistors of DS1, DS2, CM1 at the emitter current $I_e = I_0$; $I_{1.1}$, $I_{2.1}$, $I_{1.2}$, $I_{2.1}$, $I_{2.2}$ — output currents of DS1, DS2 (Fig.7); I_{CM2} — output current of CM1;

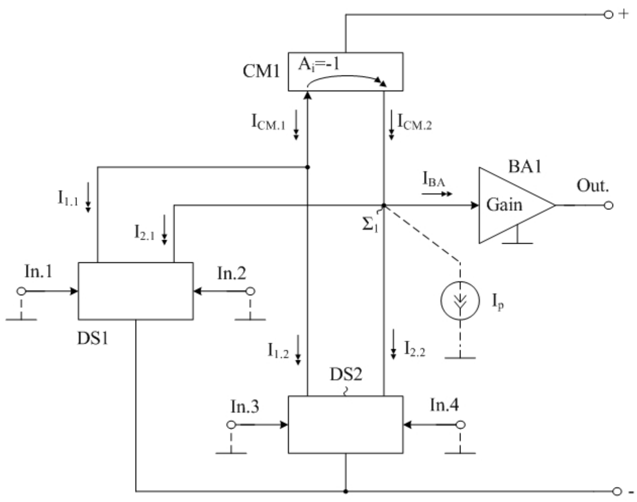

Fig. 7. The method of decreasing zero level of OA with one high-impedance node Σ_1.

$A_{pi.j}$, $A_{ni.j}$ — positive and negative integers, which characterize a weak current unbalance of the input stages DS1, DS2, connected with the effect of β gain on their operation [23, 24]; ξ_{p1},ξ_{n1} — coefficients of the weak current unbalance of the current mirror CM1, regarding zero suppression of CM1 due to the base current effect of transistors [23, 24].

For Σ_1 highimpedance node the following Kirchhoff's combined equation, which takes into account β effect on the operation of the functional nodes, is valid:

$$I_p = I_{CM2} - X_p I_{bp} - X_n I_{np} - I_{2.2} - I_{2.1}, \quad (4)$$

where I_p — independent parameter, which determines the zero level of OA [24], X_p, X_n — parameters of the buffer amplifiers BA1, which characterize the direction and the absolute values of components of its input current.

To minimize the systematic component of the offset voltage of OA of Fig. 7 (V_{io}) it is necessary to meet the following conditions

$$A_{p1.1} + A_{p1.2} + \xi_{p1} = A_{p2.1} + A_{p2.2} + X_p, \quad (5)$$

$$A_{n1.1} + A_{n1.2} + \xi_{n1} = A_{n2.1} + A_{n2.2} + X_n. \quad (6)$$

Thus, the circuit synthesis of OA with the architecture of Fig. 7, which should have low V_{io}, reduces to the rational choice of the main functional nodes of OA (DS1, DS2, CM1, BA), the coefficients of the weak current unbalance which should satisfy equations (5), (6). The versions of designing these functional nodes of OA (DS1, DS2, CM1, BA) are given in [23, 24].

Similarly, to reduce the radiation degradation of the voltage gain of classical differential cascades, special construction of reference current sources [25], adjusting the static mode of the input transistors to the specified level of the gamma radiation, is necessary.

Summary

For many tasks of tool engineering, it is reasonable to realize the production of analog ICs, processing the signals of the low-ohmic sources in conditions of simultaneous effect of low temperatures and penetrating radiation, on SiGe BTs.

SiGe n-p-n-transistors of SGB25V technology retain their amplifying properties at the temperature of liquid nitrogen and at the effect of gamma rays with the absorbed dose up to 2.1 Mrad. Besides,

- the voltage on the forward-biased base-emitter junction (the test chip SGB25V_016P) decreases in comparison with normal conditions by less than 1.03 mV within the range of the emitter currents from 100 μA up to 10 mA;

- the output small-signal resistance in the common-emitter configuration doesn't practically change;

- gamma rays strongly affect β value only in the area of small emitter currents. Therefore, providing the operating mode of the analog IC with heavy density of the emitter current, it is possible to reduce significantly the radiation-induced alteration of β;

- there is a number of circuitry techniques to minimize the effect of β degradation of the transistors from the exposure of gamma-quanta on the circuit functions, e.g. the systematic component of the offset voltage of OA [23, 24], the voltage gain [25].

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Вплив гамма-випромінювання на основні статичні характеристики SiGe транзисторів

Дворніков О. В., Дятлов В. Л., Прокопенко М. М., Чеховський В. О.

Розглянуто вплив гамма-випромінювання радіонукліда ^{60}Co на найбільш важливі для аналогових мікросхем характеристики SiGe n-p-n транзисторів техпроцесу SGB25V: напруга на прямозміщеному емітерному переході, залежність статичного коефіцієнта передачі струму бази в схемі з спільним емітером (β) від емітерного струму, вихідна характеристика в схемі з спільним емітером.

Ключові слова: радіаційна стійкість; SiGe-транзистори; аналогові мікросхеми; гамма випромінювання; основні статичні характеристики транзистора

Влияние гамма-излучения на основные статические характеристики SiGe транзисторов

Дворников О. В., Дятлов В. Л., Прокопенко Н. Н., Чеховский В. А.

Рассмотрено воздействие гамма-излучения радионуклида ^{60}Co на наиболее значимые для аналоговых микросхем характеристики SiGe n-p-n транзисторов техпроцесса SGB25V: напряжение на прямосмещенном эмиттерном переходе, зависимость статического коэффициента передачи тока базы в схеме с общим эмиттером (β) от эмиттерного тока, выходная характеристика в схеме с общим эмиттером.

Ключевые слова: радиационная стойкость; SiGe-транзисторы; аналоговые микросхемы; гамма излучение; основные статические характеристики транзистора