Original scientific paper

Informacije MIDEM
Journal of Microelectronics,
Electronic Components and Materials
Vol. 43, No. 1(2013), 27 – 40

Impact of the Excess Base Current and the Emitter Injection Efficiency on Radiation Tolerance of a Vertical PNP Power Transistor in a Voltage Regulator

Vladimir Đ. Vukić[1], Predrag V. Osmokrović[2]

[1]Institute of Electrical Engineering "Nikola Tesla", University of Belgrade, Serbia
[2]Faculty of Electrical Engineering, University of Belgrade, Serbia

Abstract: Examinations of the minimum dropout voltage with a high load current demonstrated proper operation of voltage regulators L4940V5 for gamma radiation doses of up to 500 Gy(SiO2). An increase in the minimum dropout voltage of approximately 0.5 V was measured. Due to the relatively small dissipation, the thermal protection circuit did not significantly affect the operation of the voltage regulator L4940V5. According to the line regulation characteristics, obtained after absorption of a total ionising dose of 300 Gy(SiO2), the voltage reference was negligibly affected by the irradiation. Variations in the line regulation characteristics after irradiation were less than 1% in comparison with initial values. Despite the operation with a load current of 400 mA, the serial PNP transistor emitter injection efficiency remained high after irradiation, with an estimated value greater than 0.93. The interdigitated structure of the serial transistor's base-emitter junction led to an abrupt increase of the surface recombination in a gamma radiation environment, followed by a great rise in the excess base current. This effect was enabled by the feedback circuit reaction and its influence on a driver transistor, affecting the sharp increase of the serial transistor's base current. On the other hand, the antisaturation circuit prevented a rise in the total voltage regulator's quiescent current above the limit of approximately 40 mA.

Key words: vertical PNP transistor, excess base current, collector-emitter dropout voltage, voltage regulator, emitter injection efficiency, ionising radiation.

Vpliv presežnega baznega toka in izkoristek injekcije emitorja na tolerance radiacije vertikalnega PNP močnostnega tranzistorja v napetostnem regulatorju

Povzetek: Raziskave najnižjega padca napetosti pri visokem bremenskem toku so pokazale pravilno delovanje napetostnih regulatorjev L4940V5 za gama radiacijske doze do 500 Gy(SiO2). Izmerjeno je bilo povišanje minimalnega padca napetosti za okoli 0.5 V. Zaradi relativno majhne disipacije temično zaščitno vezje ni imelo pomembnega vpliva na napetostni regulator L4940V5. Glede na regulacijske karakteristike po absorpciji ionizirajočega sevanja v višini 300 Gy(SiO2) je bil vpliv sevanja na referenčna napetost zanemarljiv. Variacije vhodnih regulacijskih karakteristik po obsevanju so bile manjše od 1 %. Pri bremenskem toku 400 mA je izkoristek injekcije emitorja serijskega PNP tranzistorja ostal visok tudi po obsevanju in je po oceni znašal 0.93. Prepletena struktura bazno-emitorskega spoja serijskega tranzistorja je vodila v nenadno povečanje površinskih rekombinacij v okolju gama žarkov, kar je povzročilo hitro in veliko prekoračitev baznega toka. Ta efekt je posledica povratne vezave in njenega vpliva na gonilni tranzistor, kar povzroča strm porast baznega toka serijskega tranzistorja. Po drugi strani antisaturacijsko vezje preprečuje porast toka nad 40 mA.

Ključne besede: vertikalni PNP tranzistor, presežni bazni tok, padec napetosti kolektor - emitor, napetostni regulator, izkoristek injekcije emitorja, ionizacijsko sevanje.

* *Corresponding Author's e-mail: vvukic@ieent.org*

1. Introduction

Recent advances in aerospace applications, especially in the development of satellite electronic devices, have attracted much attention to the operation of electronic devices in the radiation environment [1, 2]. Most of the efforts in analysing the radiation effects have been dedicated to the MOSFET-based electronic components [3, 4] necessary for the operation of these complex technical systems, such as microprocessors [3, 5], memories [3], switching power supplies [4], logical circuits [1, 6] and discrete transistors [7, 8], including electronic dosimeters [9]. Nevertheless, much attention was also dedicated to the influence of the radiation environment on electronic equipment based on bipolar transistors [2, 6], such as operational amplifiers [10–12], comparators [13, 14], and, finally, linear voltage regulators [15–17]. Research into the radiation effects in linear integrated circuits with bipolar transistors attracted much attention during the last two decades. After the discovery of enhanced-low-dose-rate sensitivity (ELDRS) in bipolar transistors [2, 18], examination of linear bipolar integrated circuits in the radiation environment became a highly interesting topic [19–21].

Beside operational amplifiers and comparators, examinations of the low-dropout voltage regulators became particularly frequent [15–17, 22, 23]. Yet, owing to the very high prices of radiation tolerant integrated circuits (ICs), requirements were imposed for the use of commercial-off-the-shelf (COTS) electronic components in aerospace and nuclear applications [4]. According to these requirements, an effort was made to detect appropriate commercial low-dropout voltage regulators suitable for use in the radiation environment. Moreover, detection of the appropriate radiation tolerant commercial technological processes, as well as definition of their preferable characteristics, was undertaken.

Gain degradation in irradiated bipolar transistors can be a significant problem, particularly in linear integrated circuits. Ionizing radiation causes the base current in bipolar transistors to increase, due to the presence of net positive charge in the oxides covering sensitive device areas and increases in surface recombination velocity [1]. When bipolar integrated circuits are exposed to ionizing radiation in space, there are two primary failure mechanisms: (1) leakage current caused by trapped positive charge in the field oxide or (2) reduction of the current gain of individual transistors [1]. Digital circuits are usually designed to be relatively insensitive to variations in current gain, so total-dose failures in digital ICs are primarily isolation-related. However, for most bipolar technologies that are used in linear integrated circuits, the total-dose failure mechanism is reduction of the current gain [1]. The forward emitter current gain degradation in bipolar transistors is caused by the interactive effects of radiation-induced charge in the oxide and increased surface recombination velocity. The charge in the oxide increases the surface potential, causing the recombination rate near the emitter-base junction of NPN transistors to increase as the electron and hole concentrations become comparable (crossover point) [1]. When the charge in the oxide is sufficient to move the recombination peak beneath the surface of the base region, additional increases in base current with total dose are quite small. Vertical PNP transistors are usually radiation tolerant because the net positive charge in the oxide accumulates the base region. Since the emitter doping in vertical PNP transistors is large compared to the base doping in NPN transistors, the effects of oxide charge on surface recombination are much less. However, lateral PNP transistors can be quite radiation sensitive because of the current-flow path near the surface [1].

A recent article on the characteristics of commercial-off-the-shelf low-dropout voltage regulators "STMicroelectronics"® L4940V5 dealt with the analysis of the complex response of irradiated integrated circuits with a negative feedback loop in the gamma radiation field [24]. Besides gamma radiation, the isolated collector vertical PNP power transistor was also seriously affected by the load current and input voltage [24–26]. The increase in load current had a major effect on the reduction of the serial transistor's current gain. Nevertheless, owing to the device's tests with a moderate load, the impact of the radiation effects in the emitter area on the serial transistor's radiation hardness could not be determined, since the power transistor certainly operated without emitter crowding. Moreover, the magnitude of the emitter injection efficiency and the influence of the particular integrated circuit's functional blocks on negative feedback reaction remained ambiguous [25]. Therefore, tests of minimum dropout voltage with high load current had to be carried out in order to acquire complete data on the examined circuit's radiation response.

Since the voltage regulators L4940V5, primarily designed for automotive applications, long ago showed significant radiation hardness [27], a new series of experiments in the radiation environment were undertaken on these integrated circuits. The primary hypothesis was that the main cause of the L4940V5 voltage regulator's high radiation hardness was the small degradation of the serial vertical PNP transistor's forward emitter current gain (β), which was mainly due to the shift of current flow from the surface towards the substrate [26, 27]. However, recent experiments, relying on examinations of the voltage regulator's quiescent current, together with the maximum output current, highlighted the increase of the serial transistor's base current and consequently, the significant decrease of its forward emitter current gain [26]. This led to the conclusion that the primary influence on the previously perceived high radiation tolerance of the L4940V5 voltage regulator is the control circuit and not the serial PNP transistor. Nevertheless, as already mentioned, it was not clear what primarily affected the rise of the power vertical PNP transistor's base current; whether it was the control circuit (negative feedback circuit reaction, activation of some protective parts of the integrated circuit) or degradation of the serial power transistor itself. A further difficulty for the necessary analysis was that it was not possible to obtain even the simplest schematic circuit diagrams of the L4940V5 voltage regulator. Therefore, defining an experiment that would enable analysis of both the serial PNP transistor and elementary blocks of the voltage regulator's control circuit, in order to obtain data on the most radiation-sensitive parts of the L4940V5 voltage regulator, without the need to unseal the integrated circuits, was a problem.

In this paper, the results presented relate to the change in the serial transistor's minimum dropout voltage, the excess base current and the forward emitter current gain in the heavily loaded voltage regulators L4940V5, operating in the γ radiation field. Also, the line regulation characteristics have been presented in order to complete the analysis of the voltage regulator's critical mode of operation, with low input voltages and high output currents.

2. Materials and methods

Integrated 5-volt positive voltage regulators L4940V5 were tested in the Vinča Institute of Nuclear Sciences, Belgrade, Serbia, in the Metrology-dosimetric Laboratory. Circuits L4940V5 were from the batch WKOOGO 408, made by "STMicroelectronics"® in China [27, 28].

As a source of γ-radiation, the ^{60}Co was used and it was situated in a device for the realisation of the γ-field, IRPIK-B. The accepted mean energy of γ-photons is E_γ = 1.25 MeV. The exposition doses are measured using a cavity ionising chamber "Dosimentor"® PTW M23361, with a volume of $3\cdot10^{-5}$ m^3. With the cavity ionising chamber, the reader DI4 was used [27].

Devices had been irradiated until the predetermined total doses were reached. Devices in the γ-radiation field were exposed to a total dose of 500 Gy, with a dose rate of 4 cGy(SiO_2)/s [26]. All measurements were performed within half an hour after the exposure.

Current and voltage measurements were carried out with laboratory instruments "Fluke"® 8050A and "Hewlett-Packard"® 3466A. All measurements and the irradiation of the components were performed at a room temperature of 20°C.

The main values used for detection of the degradation of the voltage regulator due to the exposure to ionising radiation were the serial transistor's forward emitter current gain and collector-emitter (dropout) voltage. The electrical values measured were the voltage regulator's input and output voltages and quiescent current. During the irradiation, the biased devices examined were supplied with the same input voltage, 8 V, while the load currents had three different values: 1 mA, 100 mA and 500 mA. The fourth group of irradiated devices comprised unbiased voltage regulators, without input supply voltage [24, 26].

Examination of the change in the collector-emitter (dropout) voltage on the serial transistor was performed as follows: the input voltage was increased until the output voltage dropped to 4.9 V, for a constant output current of 400 mA [27]. The difference between the input and output voltages represents the dropout voltage on the serial transistor (QS in Fig. 1) for the corresponding current.

The next step was the measurement of the output voltage and the quiescent current for an unloaded voltage regulator, with input voltage equal to the value measured on the device loaded with 400 mA, as low as necessary to reduce the output voltage to 4.9 V. In voltage regulators with the serial PNP power transistor, a quiescent current (I_q) represents a sum of the control circuit's internal consumption current and the serial transistor's base current [26]. Quiescent current for an unloaded voltage regulator (I_{q0}), with constant input voltage, was assumed to be approximately equal to the value of the loaded voltage regulator's internal consumption. Subtraction of the unloaded circuit's quiescent current from a quiescent current of devices loaded with 400 mA, for the same input voltages, gave the value of the serial transistor's base current [29].

$$I_b = I_q\Big|_{(I_C=I_{load})} - I_{q_0}\Big|_{(I_C=0)} \qquad (1)$$

The values of the quiescent currents for the unloaded voltage regulators (I_{q0}) were obtained during examination of the samples with disconnected load, with the same input voltage as previously recorded on the same devices operating with a load current of 400 mA.

The serial transistor's forward emitter current gain was determined as the quotient of the voltage regulator's output current (that is, the serial transistor's collector

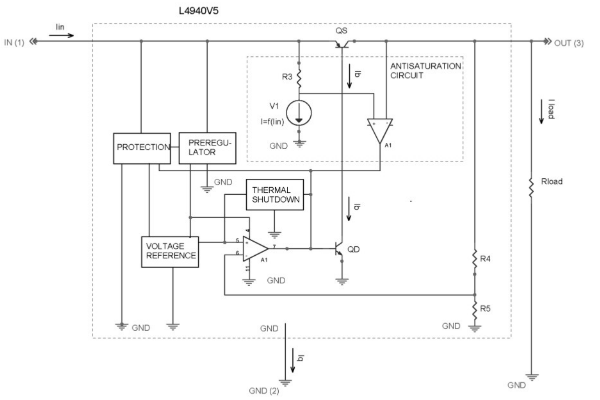

Figure 1: Schematic block diagram of the L4940V5 voltage regulator.

current on the variable resistor) and the calculated value of the base current [26, 29]:

$$\beta = \frac{\partial I_c}{\partial I_b} \approx \frac{I_c}{I_b} \tag{2}$$

During irradiation, heat sinks of the specific thermal resistance of 14 K/W were attached to the tested samples of voltage regulators [29]. When the thermal resistance junction – case (in this case the standard integrated circuit's TO-220 case equals 3 K/W) was included in the calculation, the overall thermal resistance junction – ambient of the voltage regulator L4940V5 would not exceed 17 K/W. The manufacturer declares that the usual dropout voltage is about 0.5 V with a load current of 1.5 A [28], and, also, that the maximum power dissipation is nearly 7.3 W for a heat sink of 14 K/W and ambient temperature equal to 25°C [28] (calculated for the total thermal resistance of 17 K/W and the maximum junction temperature of 150°C).

All the above-mentioned measurements were performed in joint experiments on voltage regulators, focused on maximum output current [26], minimum dropout voltage for moderately loaded devices [24, 25] and, in this paper, dropout voltage for heavily loaded samples. All three kinds of measurements were performed in the same conditions, in the order specified in this paragraph. According to the guidelines found in literature [30, 31] and previously reported uncertainties of measurement [29], the calculated combined uncertainty of measurement for the implemented experimental procedure was approximately 0.6% [25].

Besides the examination of the minimum dropout voltage and related parameters, the results of the examination of the line regulation characteristics in the voltage regulators L4940V5 were also presented. In this experiment, values of the output voltage were measured for constant output current (0A, 100 mA, 300 mA, 500 mA and 700 mA), while the input voltage had values of up to 15 V (specifically 6.5V, 8V, 10V, 12V and 15V) [27]. The resulting diagrams represent the difference between values of the output voltage recorded prior to irradiation and after exposure to the total dose of gamma radiation of 300 Gy(SiO_2). The line regulation characteristics were obtained during the primary examinations of the low-dropout voltage regulators L4940V5, so the ionising radiation dose rate differs slightly, having a value of 5.5 cGy(SiO_2)/s [27]. All the other measurement equipment, sources of radiation, dosimetry and experimental set-up were the same.

The block diagram of voltage regulator L4940V5, according to the data published in the literature [28, 32], is presented in Fig. 1. More details about the experiment, integrated circuits and implemented technological processes are provided in the references [24–29, 32].

3. Results and discussion

Figs. 2–7 present the changes in the serial transistor's dropout voltage and the forward emitter current gain for the voltage regulators L4940V5, for a constant load current of 400 mA and output voltage of 4.9 V. The total dropout voltage rise (*i.e.*, increase of the collector – emitter voltage of the serial transistor QS, Fig. 1) following the gamma radiation absorption of 500 Gy(SiO_2) was approximately 0.5–0.6 V (Fig. 2). Initial values of the measured minimum dropout voltage, obtained using precise laboratory sources and for a load current of 400 mA, were approximately 0.23 V. On the other hand, simultaneously with the moderate rise of the serial transistor's dropout voltage, an abrupt decrease of the serial transistor's forward emitter current gain (*β*; Fig. 3) was recorded. Some important questions needed answers in the attempted research: is the perceived decrease of the serial transistor's current gain a consequence of the feedback circuit reaction, only affecting the serial transistor's operation point without a real sharp decrease of its forward emitter current gain? Either the main cause of the voltage regulator's reaction may be sudden activation of some of the protective circuits, such as the thermal shutdown or antisaturation circuit. Or the serial transistor itself primarily affected the complete integrated circuit's operation owing to the change of operation mode or sudden decrease of the emitter injection efficiency.

A standard procedure to obtain answers to the questions posed could be to implement a simulation model for the integrated circuit. However, unfortunately, the manufacturer did not provide any detailed schematic

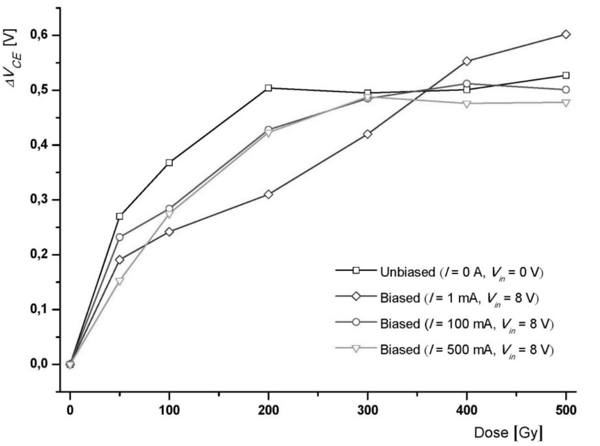

Figure 2: Change in the mean serial transistor's minimum dropout voltage in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA).

circuit diagram either in the datasheet [28] or in articles [32] or patents [33] regarding the voltage regulator L4940V5. Beside the simple block diagram [28], presented also in Fig. 1, some details were provided about the antisaturation circuit [32], but this was not nearly enough to create a detailed simulation model. Therefore, analysis of the primary mechanisms of the degradation of the L4940V5 voltage regulator would have to rely on the available experimental data, both as presented here and as previously reported [26, 27, 29].

In the paper related to the analysis of the L4940V5 voltage regulator's maximum output current, it was perceived that, despite the integrated circuit's significant radiation hardness, its vertical serial power transistor was more sensitive than expected [26]. The main cause of the sharp rise in the serial transistor's base current was identified as the interdigitated structure of the isolated collector vertical PNP transistor. This structure affected the great rise in the serial transistor's base current as a consequence of the increased surface recombination processes along the base-emitter junction, due to its high perimeter-to-area ratio [26]. Increase in the injection level leads to decrease of the surface recombination contribution and decreased degradation of the forward emitter current gain. The results obtained for the heavily loaded voltage regulators, shown in Fig. 3, also lead to the conclusion that the dominant influence on the radiation response of the moderately loaded devices has the negative feedback reaction [24].

The previous paper examined the minimum dropout voltage of the L4940V5 voltage regulator with a constant load current of 100 mA [24]. Compared with the previously noticed decline in the forward emitter current gain by 30–80 times [24], now the registered decline of the current gain was no greater than 6–9 times (from 70–105 down to approximately 12; Fig. 3). A nearly sevenfold increase in the base current and its saturation on the level of approximately 35 mA (Fig. 7) also leads to the hypothesis that the primary cause of the seemingly sharp decline of the serial transistor's forward emitter current gain was the very strong influence of the control circuit, primarily by the change in the serial transistor's base current. The interpretation of the observed phenomenon is the same as in the case of moderately loaded devices: a sevenfold decline in the forward emitter current gain of the PNP power transistor (for the same values of the base-emitter voltage) did not occur, but the negative feedback reaction caused a shift in the voltage regulator's operating point on the characteristic $\beta(I_C)$ of the serial transistor.

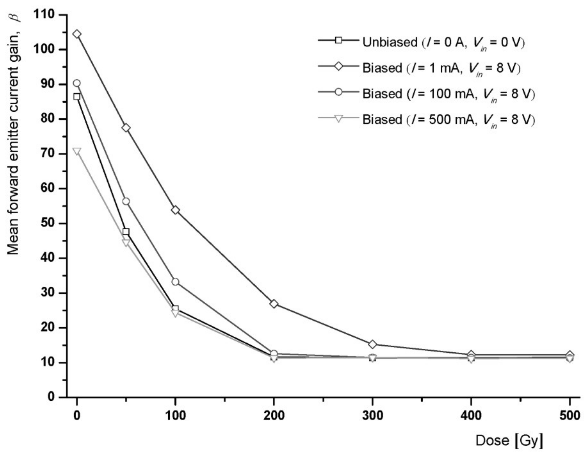

Figure 3: Change in the mean serial transistor's forward emitter current gain in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA).

However, the data presented in Figs. 3 and 4 are a clearer illustration of the previously reported comment – the same devices, after the same total ionising doses, operated with a forward emitter current gain of approximately 12 (for I_{load} = 400 mA), compared with the cases of moderately loaded devices (I_{load} = 100 mA), where measured values of the current gain declined down to 2–3 [24]. Yet, it should be mentioned again that the measured values of the serial transistor's forward emitter current gain were not obtained for the same values of the base – emitter voltage (V_{BE}), but rather the quotient of the measured collector and base currents (equation (2)) of the serial device QS (Fig. 1) during the experiment.

Since a simulation model of the L4940V5 voltage regulator could not be created, confirmation of the presented hypothesis on the primary influence of the feedback circuit on measured values of the serial transistor's current gain have to be obtained by eliminating the

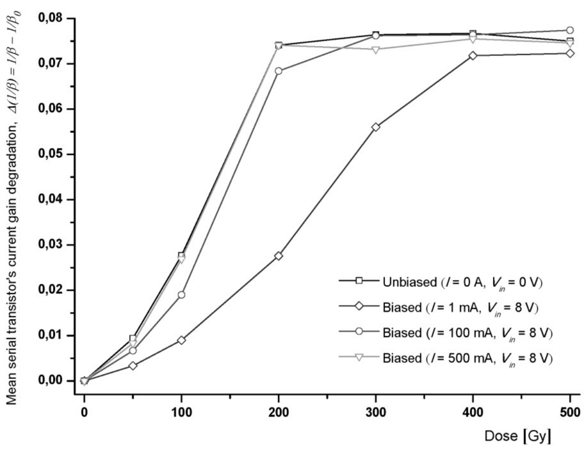

Figure 4: Change in the mean serial transistor's current gain degradation in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA).

dominant influence of all the other functional blocks in the voltage regulator. These blocks are, as presented in Fig. 1, the preregulator with protection circuitry (thermal protection, overload protection, shutdown circuit, etc.), the antisaturation circuit, the feedback circuit with operational amplifier and, finally, the serial PNP power transistor. Now the influence of particular functional blocks on the radiation hardness of the L4940V5 voltage regulator will be analysed, with particular attention to the exploitation characteristics of the serial vertical PNP transistor.

The saturation boundary of the serial transistor's base current was approximately 35 mA. This value is nearly the same as the base currents observed during examination of the maximum output current [26]. During the same tests, the values of the serial PNP transistor's forward emitter current gain were measured, being in the range of approximately 20–25. The presented analysis leads to the conclusion that a rise in the output current from 400 mA up to 700–800 mA would have led to characteristics similar to those obtained during examination of the voltage regulator's maximum output current [26], with a slightly lower measured current gain, similar values of the base current and minimum influence of the negative feedback reaction. Values of the base currents presented in Fig. 7 were obtained by subtracting the voltage regulator's quiescent currents without load (Fig. 6) from the total voltage regulator's quiescent currents (Fig. 5).

In the case of a high load current of 400 mA, there was little difference between the curves depending on the bias conditions. Owing to the requirement for the voltage regulator to provide much higher output current than during the previous tests, regardless of the bias conditions, the base currents quickly rose to the saturation value of 35 mA (Fig. 7). However, the rise in the base current for biased devices with negligible load current (V_{in} = 8 V, I = 1 mA) was the slowest.

The obvious limits of the voltage regulator's quiescent current (up to 40 mA; Fig. 5) and the serial PNP transistor's base current (up to 35 mA; Fig. 7) are consequences of the applied antisaturation circuit (Fig. 1). In the voltage regulator L4940V5 a circuit is included which prevents intrinsic saturation of the PNP transistor, eliminating quiescent current peaks [32]. Following the bias of the isolated collector power PNP transistor operating in the saturation mode, a current is observed to flow to the substrate. The reason was the triggering of the parasitic PNP transistor whose collector is the substrate. The forward emitter current gain of this parasitic element is $\beta = 2 - 4$, but it can drain a considerably larger current if the power PNP transistor is forced into very deep saturation [32]. This is the case when the regulator is starting with a small load and the driver is supplying the maximum current at the base of the vertical PNP transistor. In these conditions, for a load current of nearly 1 mA, the PNP power transistor's base current may be 100 mA, while the substrate quiescent current could reach 300 mA [32]. To prevent this effect, an antisaturation circuit has been incorporated into the device. This circuit prevents the emitter-collector voltage of the PNP transistor from falling below the predetermined level of the input current due to the limitation of the serial transistor's base current, preventing the saturation of the PNP power transistor [32].

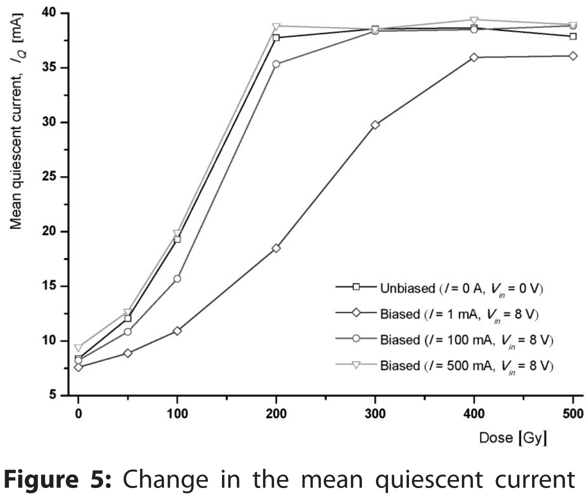

Figure 5: Change in the mean quiescent current in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA).

Soon after the start of irradiation, the serial transistor's base current begins to rise, affected by the load current and input voltage. The process is shown in Fig. 7 and is related to amount of the absorbed total ionising dose rather than the time-dependency effects during irradiation. After a total dose of 200 Gy(SiO_2), for most of the examined samples the base current reached the limit, primarily as a consequence of the antisaturation circuit reaction. The effect of the antisaturation circuit becomes explicitly represented during the operation with a high load current. If the antisaturation circuit did not react, the rise in the serial transistor's excess base current and, consequently, the voltage regulator's quiescent current would be much more marked.

The effect of the negative feedback reaction in a low-dropout voltage regulator is to preserve the stable output voltage, and conserve the minimum possible dropout voltage, quiescent current and chip temperature. Since the heavily loaded samples of voltage regulators L4940V5 operated with output current of 400 mA, which is nearly a quarter of the declared maximum current of examined integrated circuit and approximately half of the measured values of the maximum output current, problems on the circuit's overload were not related to this case. Hence, the voltage regulator's control circuit had to balance the influences of ionising radiation on the quiescent current and the serial transistor's dropout voltage. Although devices L4940V5 are low-dropout voltage regulators, primarily designed for operation with the minimum voltage collector-emitter on the serial transistor, an excessive rise in the quiescent current and, therefore, the serial transistor's base current may lead the power PNP transistor into saturation mode, threatening the correct operation of the voltage regulator as a linear integrated circuit. Therefore, prevention of an excessive increase in the voltage regulator's quiescent current is a priority, even in the low-dropout voltage regulator. This preferential reaction of the antisaturation circuit is clearly noticeable in Figs. 5 and 7, being directly connected with the increase in the serial transistor's dropout voltage after the absorption of the total doses of 200–300 Gy(SiO_2) (Fig. 2).

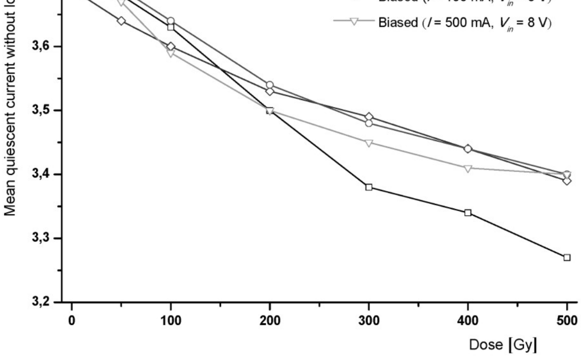

Figure 6: Change in the mean quiescent current in the unloaded voltage regulator L4940V5 under the influence of γ-radiation ($V_{in} = V_{CE(400\,mA)} - 4.9$ V, $I_{out} = 0$ A).

From early examinations of the radiation effects in voltage regulators L4940V5, line regulation characteristics for unbiased and biased samples after the absorption of the total dose of gamma radiation of 3 kGy(SiO_2) were published [27]. A group of five samples was exposed to gamma radiation with a dose rate of 5.5 cGy(SiO_2)/s [27]. Despite the influence of γ radiation, in a wide range of the input voltages and load currents, the output voltage expressed very moderate change, measured only in tens of millivolts [27].

In this paper we presented results of examination of the voltage regulator's line regulation characteristics from the same primary experiment, but after absorption of a ten times lower dose than presented in the previous article [27]. This was nearly on the half of the range of 500 Gy(SiO_2) used in the experiment described in this paper. Samples were analysed after the absorption of the total gamma radiation dose of 300 Gy(SiO_2). Line regulation characteristics obtained without bias during the irradiation were presented in Fig. 8, while Fig. 9 showed the line regulation characteristics of devices that operated with input voltage V_{in} = 7 V and output current I_{load} = 100 mA in a gamma radiation environment. In these cases, changes in the line regulation characteristics were symbolic, being in the range of millivolts. Some greater variations of the output voltage could only be perceived for the operation modes with lower input voltages (6.5 V and 8 V) and higher load currents (from 300 mA up to 700 mA). Nevertheless, the maximum variations of the output voltage after absorption of the total dose of 300 Gy(SiO_2) did not exceed 40 mV, which is less than 1% of the nominal output voltage.

Other useful information obtained from the line regulation data is related to the voltage reference. Since variations of the output voltage for load currents up to 100 mA are only a few millivolts, regardless of the input voltage, they are a good indication that the degradation of the voltage reference is negligible. Slightly higher variations of the output voltage from the nominal value of 5 V were recorded for higher load currents and lower input voltages, yet in all cases within the boundaries of ±1% around the nominal value. These minor variations of the output voltage represent verification of the proper operation of the negative feedback circuit and particularly the operational amplifier A1 (Fig. 1).

As mentioned earlier, the attached heatsinks enabled the voltage regulators to operate with power dissipations exceeding 7 W. In the events presented in the literature [23, 33], the high chip temperature led to early activation of the thermal protection circuit and the reduction of the voltage regulator's output current. On the other hand, examinations of the minimum dropout voltage on the serial transistor, with constant load current of 400 mA, were always in operation modes with low dissipation, never exceeding 1 W. Therefore, analysis of the line regulation characteristics enabled both estimation of the thermal shutdown circuit on the voltage regulator's operation, and the integrated circuit's operation with low input voltages and higher load currents.

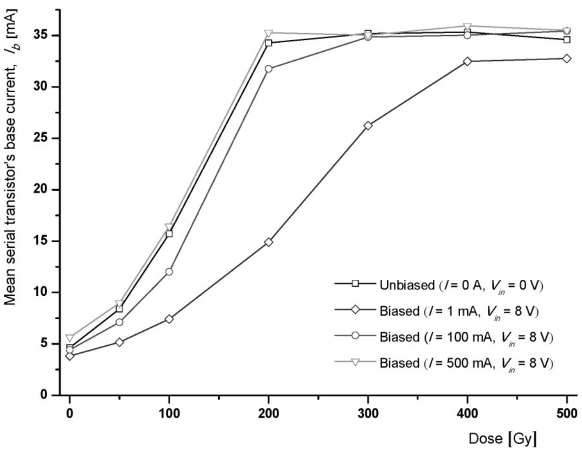

Figure 7: Change in the mean serial transistor's base current in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA).

While obtaining the line regulation characteristics, the L4940V5 voltage regulator successfully operated with both low dissipations and power dissipations up to 7 W (for V_{in} = 15 V, I_{load} = 700 mA; Figures 8 and 9). As may be seen from Figures 8 and 9, there were no problems during the voltage regulator's operation that would activate the thermal shutdown circuit, affecting the operation of the serial transistor QS and the entire integrated circuit. Therefore, power dissipations significantly below the threshold of 1 W would certainly not have any effect on the thermal shutdown circuit during examination of the minimum dropout voltage, eliminating its potential influence on the sharp rise in the serial transistor's base current, I_b (Fig. 1).

Examination of the minimum dropout voltage in the heavily loaded voltage regulators L4940V5 was expected to lead to manifestation of the mechanism of the serial PNP transistor's emitter crowding. Very sharp saturation of the base current was evident even for doses of 200 Gy(SiO_2), as may be seen in Fig. 7. The mechanism of emitter crowding may lead to a great decline in the serial transistor's forward emitter current gain, affecting the rise in the base current.

Due to the operation of tested samples with a high load current, the emitter depletion mechanism was expected to have greater influence than in samples operating with less than 10% of the serial transistor's nominal current. Results obtained during the examinations of the moderately loaded samples clearly demonstrated the strong influence of the load current during irradiation on the serial transistor's excess base current [24]. In the case of heavily loaded devices, all types of irradiation are followed by the detection of the minimum dropout voltage with a high load current of 400 mA. Therefore, additional data on the influence of high load current on the radiation tolerance of the vertical PNP power transistor were expected.

Despite the difficulties in estimating the transistor's physical parameters in an integrated circuit, especially due to their significant changes during the radiation exposure, some data, on the technological process and the main characteristics of the vertical PNP power transistor, enabled estimation of the emitter injection efficiency. Consequently, evaluation of the emitter crowding and its influence is possible, also as an estimation of the emitter depletion mechanism on the radiation hardness of the serial transistor in the voltage regulator L4940V5.

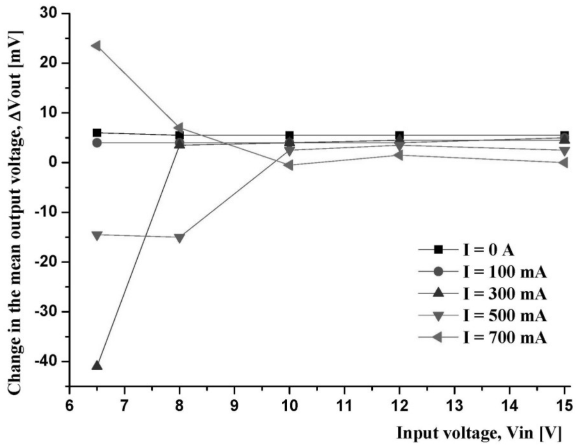

Figure 8: Relative line regulation characteristics of the unbiased voltage regulators L4940V5 after deposition of the total dose of γ-radiation of 300 Gy(SiO_2) (bias conditions: Vin = 0 V, I = 0 A).

Now, the principal characteristics of the isolated collector vertical PNP power transistor in the voltage regulator L4940V5 have to be estimated. Therefore, data on the implemented technological process and construction of the integrated circuit L4940V5 have to be analysed.

The implemented serial element is the isolated collector PNP power transistor (ICV PNP) [29], created from 36 groups of elementary interdigitated PNP transistors made by "HDS²/P²"® Multipower 20 V ("High Density Super Signal / Power Process") [27, 34]. The vertical PNP transistor is created with the isolated collector (a graded collector with the p enhancement region) and the nested emitter (a p type, with the phosphorous impurities, $Q_p \approx 5{\cdot}10^{13}$ cm^{-2}). Also, a graded base was

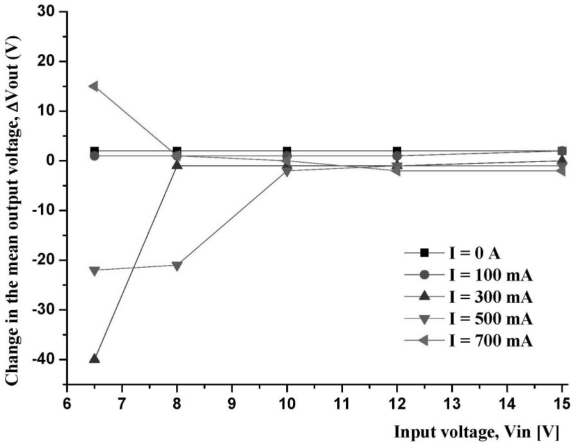

Figure 9: Relative line regulation characteristics of the biased voltage regulators L4940V5 after deposition of the total dose of γ-radiation of 300 Gy(SiO_2) (bias conditions: Vin = 7 V, I = 100 mA).

implemented (n+ area near the base contact, with arsenic impurities, $Q_{As} \approx 5\cdot10^{15}$ cm^{-2}, together with the n type volume of the base surrounding the emitter, with boron impurities, $Q_B \approx 2\cdot10^{13}$ cm^{-2}) [27, 34]. After synthesis of the semiconductor structure was completed, an insulating layer made of silicon-dioxide was deposited above the wafer, followed by another layer of silicon-dioxide implanted with phosphorous and boron (Phosphorous Boron Silicon Glass, PBSG). Both layers had a thickness of 500 nm [27, 34].

For the exact determination of the doping densities of the emitter and base areas, it would be necessary to obtain exact data on the effective width of their layers. However, such data are not provided by the examined references [32, 34]. Nevertheless, the base width can be estimated from the gain-bandwidth product, f_T (the product of the common emitter current gain β and the frequency of measurement at which the gain-frequency curve begins to descend) [35]. Since the gain-bandwidth product for the ICV PNP transistor is f_T = 80 MHz [32], from the table for the calculation of a base width from the approximate gain-bandwidth product in reference [35], the active base width may be estimated to be approximately 2.25 μm. If the effective emitter length was rated as 1.5 μm, and also according to the known initial values of total quantity of impurities per unit area in the emitter and active base area ($Q_P \approx 5\cdot10^{13}$ cm^{-2} and $Q_B \approx 2\cdot10^{13}$ cm^{-2}) [34], the rated surface doping densities in the emitter and active base area before irradiation are $N_E = 3.3\cdot10^{17}$ cm^{-3} and $N_B = 9\cdot10^{16}$ cm^{-3}, respectively.

Therefore, estimated values of the base width (W_B) and the impurity concentrations in the emitter (N_E) and base (N_B) areas, as well as the thermal voltage V_T (equal to 26 mV at room temperature [36]) may be used in the calculation. The equation for the diffusion constant for the holes in the n type base area is [37]:

$$D_B = V_T \mu_p \tag{3}$$

The equation for the diffusion length of the holes in the base area is [37]:

$$L_B = \sqrt{D_B \tau_B} \tag{4}$$

From the relation for the estimation of the holes' lifetime in the n type base area [38]:

$$\tau_B = \frac{5\cdot10^{-7}}{1+2\cdot10^{-17}\cdot N_B} \tag{5}$$

as well as from equations (3) and (4), the holes' diffusion length in the base area on L_B = 12.6 μm may now be defined (mobility of holes in the n type base area obtained from the diagram on the mobility of holes in silicon, at 300 K, as $\mu_p = 340\ \frac{cm^2}{Vs}$ [38]; therefore, the diffusion constant would be $D_B = 8.84\ \frac{cm^2}{s}$, while the holes' lifetime in the n type base area would be $\tau_B = 1.8\cdot10^{-7}$ s).

The next step is the estimation of the base transport factor for a transistor with a narrow base [36]:

$$\alpha_T \approx 1 - \frac{W_B^2}{2L_B^2} \tag{6}$$

Using the obtained data on the base width (W_B = 2.25 μm) and the holes' diffusion length (L_B = 12.6 μm), from equation (6) the base transport factor prior to irradiation as α_T = 0.984 may be calculated.

From the relations on the common base current gain, α_F is [37]:

$$\alpha_F = \gamma\, \alpha_T \tag{7}$$

where γ is the emitter injection efficiency. Also, from the current ratio that defines the common base current gain, α_F (the collector current is the voltage regulator's L4940V5 output current and the emitter current is the device's input current, i.e. the sum of the collector current and the serial transistor's base current) [37]:

$$\alpha_F = \frac{I_C}{I_E} \tag{8}$$

So, finally, the common base current gain, for the serial PNP power transistor before irradiation as $\alpha_F = 0.99$ may be calculated from equation (8) (evaluated for the samples with input voltage of 8 V and output current 1 mA; in this case, the serial transistor's base current was approximately 4 mA (Fig. 7)).

Nevertheless, a correction now has to be made in the calculation of the base transport factor, α_T, obtained from equation (6). Since the $\alpha_F = 0.99$, according to equation (8), and $\gamma \leq 1$, consequently the base transport factor cannot be $\alpha_T = 0.984$, but at least 0.99. Therefore, the approximation written in equation (6) was in this case slightly inaccurate, as was the second iteration regarding the calculation of some basic parameters. If the holes' diffusion length remained the same at room temperature prior to irradiation ($L_B = 12.6$ µm), then, according to equation (6), for the initial value of the base transport factor before irradiation being $\alpha_T = 0.99$, the active base width would be $W_B = 1.8$ µm. In accordance with the result on the base width, also some other parameters may be recalculated from equations (3)-(6) in the second iteration: the doping density in the active base area before irradiation is $N_B = 8.65 \cdot 10^{16}$ cm^{-3}, the holes' lifetime in the n type base area is $\tau_B = 1.83 \cdot 10^{-7}$ s and the effective emitter length may be rated as 1.45 µm. However, despite the significant difference between the active base width in the first and second iterations (approximately 20%), the other three parameters did not demonstrate notable variations (up to 4%).

The calculated value of the emitter injection efficiency points to very efficient operation of the emitter, close to the ideal situation before exposure to γ radiation.

The worst case for emitter injection efficiency after absorption of the total dose of 500 Gy(SiO_2) would be preservation of the base transport factor, α_T, on its initial value of 0.99. However, in reality, this is not the case, since the mobility and lifetime of holes decline in the radiation environment [37]. Irradiation to 500 Gy(SiO_2) will lead to degradation of α_T and it is certainly not correct to assume it to have a constant value. Yet, for a quick evaluation of emitter injection efficiency this is a good assumption, since the exact value of the emitter injection efficiency may only be greater than estimated. In general, the reduced α_T may not have a huge impact on the radiation response. Accordingly, from Fig. 6 it may be perceived that the base current is nearly 35 mA in the worst case, for the constant collector current of 400 mA. Hence, from the data on the mentioned collector current and the emitter current (435 mA; sum of the serial PNP transistor's base and emitter current), from equation (8) the value of the common base current gain $\alpha_F = 0.92$ may be calculated. From equation (7), as well as from the obtained value of the common base current gain, the minimum emitter injection efficiency of the serial PNP power transistor after irradiation of the voltage regulator L4940V5 as $\gamma = 0.93$ may be estimated.

This is a higher value of the emitter injection efficiency than expected, and seeing the gamma radiation effects on the decrease of the base transport factor, it would be even greater. Therefore, despite the operation of the voltage regulator's serial transistor with a high current density and the abrupt rise in the base current, emitter crowding in the voltage regulators L4940V5 loaded with 400 mA was not a significant manifestation. Accordingly, the mechanism of the emitter depletion had a minor influence on the serial power PNP transistor's radiation tolerance. Nevertheless, neither thermal protection, nor the overload protection or voltage reference circuit exerted any significant influence on the radiation hardness of the serial PNP transistor. On the other hand, the antisaturation circuit had a significant impact on the voltage regulator's operation, reducing the rise in the serial transistor's excess base current. Therefore, by eliminating the influence of the mentioned functional blocks (voltage reference, protection circuits), as well as the emitter crowding of the serial transistors, it may be concluded that the interdigitated structure of the serial transistor's base-emitter junction led to an abrupt increase of the surface recombination in a gamma radiation environment. The spread of the space-charge region along the high perimeter base-emitter contact increased recombination in the base area, affecting the rise of the serial power transistor's base current. A high perimeter-to-area ratio enables the reduction of base spreading resistance and, consequently, emitter crowding, but makes transistors very susceptible to degradation due to exposure to ionising radiation, mainly because of the large area of the base-emitter junction. Regardless of its high value, the emitter injection efficiency is not equal to 1. Therefore, a portion of the reduced collector current might be attributed to recombination in the neutral base. The reduced collector current due to neutral base recombination causes the base current to increase while leaving the emitter current constant [39].

Along with an increase of surface recombination, the great rise in the excess base current was enabled by the feedback circuit reaction and its influence on the driver transistor QD (Fig. 1), affecting the sharp increase of the serial transistor's QS base current, I_b (Fig. 1). On the other hand, the antisaturation circuit prevented the total voltage regulator's quiescent current rising above the limit of approximately 40 mA. Therefore, the measured values of the forward emitter current gain were higher as the load current increased, pointing to a shift in the voltage regulator's operating point on the characteristic $\beta(I_C)$ of the serial transistor, rather than to the multiple decline of the serial transistor's current gain.

After completion of irradiation, a brief isothermal annealing at room temperature was performed. This annealing, lasting half an hour, highlighted the relatively quick recovery, which was particularly manifested through the decrease of the quiescent current during the annealing process. After examination of the irradiated integrated circuits, performed nearly one year later, the characteristics of the irradiated L4940V5 voltage regulators were similar to those prior to irradiation. Therefore, there was more expressed annihilation of defects following the irradiation than the appearance of long-term degradation of the L4940V5 voltage regulators. The effects of ionising radiation are mostly expressed through the charging of irradiated insulators, creating trapped charge that is mostly temporary. Nevertheless, irradiated silicon devices can never completely recover from the influence of gamma radiation, because the ionising radiation will knock electrons off atoms in an insulator in order to create electron–hole pairs. Therefore, during repeated exposure to ionising radiation, the failure threshold of previously irradiated integrated circuits might be much lower.

None of the examined samples of L4940V5 voltage regulators showed the output voltage falling below the threshold of 4.9 V, or of an excessive change of the serial transistor's dropout voltage. However, not all the obtained results were as expected prior to starting the examination. It was expected that the emitter injection efficiency would be significantly less than was measured, after operation with a high load current in a radiation environment. Emitter crowding was not an expected effect in the case of the serial PNP transistor in the L4940V5 voltage regulator. This was clearly a demonstration of the adequacy of the implemented interdigitated structure of the power transistor. However, the mentioned structure of the serial PNP power transistor with high perimeter-to-area ratio, led to the greatest deviations from the specified limits for IC requirements under the tested range of irradiation. The major variation from the specified characteristics of the L4940V5 voltage regulator under the tested range of irradiation was related to the sharp rise of the quiescent current. While the maximum tolerable value for the average L4940V5 device is approximately 5 mA [28], the quiescent current of the irradiated samples reached 40 mA. This significant increase, as mentioned earlier, was a consequence of the interdigitated emitter of the power transistor, leading to the increase of its base current. Nevertheless, this effect did not have a decisive influence on the operational characteristics of the L4940V5 voltage regulator; together with the rise of the dropout voltage of 0.5 V, it led to only a minor increase of the integrated circuit's dissipation. In general, the tested device remained functional after absorption of 500 Gy(SiO_2) of gamma radiation but with potentially reduced autonomy if it was used for powering battery-supplied electronic devices in a radiation environment.

As mentioned in introduction section, the examination of voltage regulators has been performed in several papers [15–17, 22, 23, 33]. The devices with power PNP transistors with round emitters, most often examined, were those such as "Micrel" 29372 [16, 23]. Much effort has been devoted to define satisfactory technological processes for use in radiation environments, in order to replace specifically designed radiation-tolerant electron devices with low-cost commercial components. According to data published in the literature, other authors have not performed radiation tests on the "STMicroelectronics" L4940V5 five-volt low-dropout voltage regulators. However, "STMicroelectronics" have made the L4913 adjustable voltage regulator, specifically designed for operation in radiation environments [40]. Therefore, a comparison could be made between data obtained for the L4940V5 commercial-off-the-shelf (COTS) voltage regulator, designed for the automotive environment and the L4913 radiation-hard voltage regulator.

Both circuits were made by the same manufacturer, "STMicroelectronics". The L4913 is a 14-pin low-dropout, positive adjustable voltage regulator with thermal shut down, overcurrent protection and external shutdown control. This device is fabricated using the "STMicroelectronics" high-speed complementary bipolar process [40]. Irradiation was performed in a ^{60}Co gamma radiation field with high (62 cGy(SiO_2)/s) and low dose rates (0.01 cGy(SiO_2)/s) [40]. Samples of the L4940V5 voltage regulators were also exposed to the ^{60}Co gamma radiation field but with a medium dose rate of 4 cGy/s. During irradiation, the input voltage of the L4913 biased circuits was set at 10 V and the output voltage set at 6 V (adjustable), while the load current was 100 mA (for the L4940V5: V_{in} = 8 V, V_{out} = 5 V (fixed value), while I_{load} had three values: 1, 100 and 500 mA). Some samples of both L4913 and L4940V5 were irradiated without bias voltage and load current. The L4913 devices were exposed to a total ionising dose of 3 kGy(SiO_2) [40], whereas the L4940V5 voltage regulators were exposed to a total dose of 500 Gy(SiO_2) (it must be mentioned that during the primary tests, the L4940V5 devices were also exposed to a total ionising dose of 3 kGy(SiO_2) [27]).

During the tests in the gamma radiation fields, the L4913 circuits proved highly radiation tolerant. The minimum dropout voltage increased by only 15–20 mV (after absorption of 500 Gy(SiO_2), depending on bias conditions, for the load current of I = 200 mA [40]. This was much less than the 500–600 mV measured on the circuits of the commercial L4940V5. However, the decrease in the maximum output current was approximately 15 mA (also after deposition of 500 Gy(SiO_2)), which is close to the 20–35 mA value measured on the L4940V5 voltage regulators [26]. Another similarity between the radiation responses was observed in the output voltages of the L4913 and L4940V5 devices. In both cases, for negligible load currents (1 mA and 5 mA), variations of the output voltage during irradiation were in the range of a few millivolts [25, 40]. Therefore, the commercial L4940V5 demonstrated a much higher increase in dropout voltage than its radiation-tolerant counterpart, the L4913; however, differences in the maximum output currents and output voltages were minimal. In general, radiation-induced damage in the L4913 voltage regulator, for doses up to 3 kGy(SiO_2), was negligible and was significantly less than that for the case of the commercial L4940V5 device. On the other hand, the L4940V5 automotive voltage regulators remained completely functional in the γ radiation field. If the dropout voltage of 500–600 mV was not critical for consumers, the L4940V5 voltage regulator would be completely suitable for the power supply of electronic devices in a ^{60}Co environment, for total doses up to 500 Gy(SiO_2).

Finally, a complete comparison of the results obtained from these two types of voltage regulators could not be performed because the authors of [40] did not observe the L4913 voltage regulator's quiescent current and accordingly, could not present results on the serial transistor's forward emitter current gain and base current. On the other hand, these detailed examinations, regarding the serial power transistor, were done for the L4940V5 voltage regulators. However, McClure and associates [40] came to the conclusion, similar to that which we arrived at for the L4940V5 device, that the damage mechanism of the L4913 voltage regulator was not the loss of the serial transistor gain but more likely to be radiation-induced error in the current sense circuit [40].

4. Conclusion

New data recorded during tests of voltage regulators L4940V5 with a load current of 400 mA showed a decline in the serial vertical PNP transistor's forward emitter current gain of 6–9 times, decreasing the value of the current gain to approximately 12. The dropout voltage on the serial PNP transistor increased approximately 0.5-0.6 V after absorption of the total gamma radiation dose of 500 Gy(SiO_2).

A significant decline in the measured values of the serial power transistor's forward emitter current gain was affected by the abrupt rise in the PNP transistor's base current. Negative feedback reaction in this case caused a shift in the serial transistor's operating point on the $\beta(I_C)$ characteristic. The main reason for the excess base current was implementation of the high perimeter-to-area ratio of the base-emitter junction in the serial PNP power transistor. The major reason for the limited increase of the serial transistor's base current was reaction of the antisaturation circuit, having the primary function to prevent an excessive rise in the quiescent current and keep the serial transistor's operation in the direct active region, and simultaneously keeping the output voltage on the referent value. The principal method for realisation of the negative feedback reaction in the voltage regulator L4940V5 was the effect of the feedback circuit's operational amplifier on the driver transistor, indirectly affecting the serial PNP transistor's base current. According to the line regulation characteristics, obtained after absorption of the total ionising dose of 300 Gy(SiO_2), also the voltage reference was negligibly affected by the irradiation. Variations in the line regulation characteristics after irradiation were expressed in terms of millivolts, being below 1% in comparison with the initial curves. Correct operation of the irradiated voltage regulators during the acquisition of the line regulation characteristics with a power dissipation of up to 7 W on the serial transistor demonstrated the minor influence of the thermal protection circuit on the results obtained. Examinations of the heavily loaded samples of voltage regulators L4940V5 in a gamma radiation field identified relatively little difference between the recorded curves regarding the serial transistor (minimum dropout voltage, forward emitter current gain, base current) for different load currents during the irradiation.

Measurement of the serial transistor's currents, together with the estimation of the physical parameters of the isolated collector vertical PNP transistor, led to the evaluation of the emitter injection efficiency being greater than 0.93 after the circuit's irradiation with a total ionising dose of 500 Gy(SiO_2). This result led to the conclusion that, even during the operation of the serial transistor with high current density, emitter crowding was not a significant factor, leaving emitter depletion as the mechanism of secondary influence on radiation tolerance of the isolated collector vertical PNP power transistor.

Acknowledgement

This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia under the project 171007, "Physical and functional effects of the interaction of radiation with electrical and biological systems".

References

1. R.D. Schrimpf, Recent advances in understanding total-dose effects in bipolar transistors, IEEE T Nucl Sci. 43 (1996) 787-796.
2. R. L. Pease, R. D. Schrimpf, D. M. Fleetwood, ELDRS in bipolar linear circuits: a review, IEEE T Nucl Sci 56 (2009) 1894-1908.
3. T.R. Oldham, F.B. McLean, Total ionizing dose effects in MOS oxides and devices, IEEE T Nucl Sci 50 (2003) 483-499.
4. H.L. Hughes, J.M. Benedetto, Radiation effects and hardening of MOS technology: devices and circuits, IEEE T Nucl Sci 50 (2003) 500-521.
5. H.J. Barnaby, Total-ionizing-dose effects in modern CMOS technologies, IEEE T Nucl Sci 56 (2009) 3103-3121.
6. R.L. Pease, Total ionizing dose effects in bipolar devices and circuits, IEEE T Nucl Sci 50 (2003) 539-551.
7. S.M. Đorić-Veljković, I.Đ. Manić, V.S. Davidović, D.M. Danković, S.M. Golubović, N.D. Stojadinović, Annealing of radiation-induced defects in burn-in stressed power VDMOSFETs, Nucl Technol Radiat 26 (2011) 18-24.
8. M.M. Pejović, M.M. Pejović, A.B. Jakšić, Radiation-sensitive field effect transistor response to gamma-ray irradiation, Nucl Technol Radiat 26 (2011) 25-31.
9. M.M. Pejović, S.M. Pejović, E.Ć. Dolićanin, Đ. Lazarević, Gamma ray irradiation and post-irradiation at room and elevated temperature response of pMOS dosimeters with thick gate oxides, Nucl Technol Radiat 26 (2011) 261-265.
10. J. Boch, F. Saigne, R.D. Schrimpf, J.R. Vaille, L. Dusseau, S. Ducret, M. Bernard, E. Lorfevre, C. Chatry, Estimation of low-dose-rate degradation on bipolar linear integrated circuits using switching experiments, IEEE T Nucl Sci 52 (2005) 2616-2621.
11. A. Johnston, R. Swimm, R.D. Harris, D. Thorbourn, Dose rate effects in linear bipolar transistors, IEEE T Nucl Sci 58 (2011) 2816-2823.
12. V. Agarwall, V.P. Sundarsingh, V. Ramachandran, A comparative study of gamma radiation effects on ultra-low input bias current linear circuits under biased conditions, IEEE T Nucl Sci 52 (2005) 510-518.
13. M.R. Shaneyfelt, J.R. Schwank, D.M. Fleetwood, R.L. Pease, J.A. Felix, P.E. Dodd, M.C. Maher, Annealing behaviour of linear bipolar devices with enhanced low-dose-rate sensitivity, IEEE T Nucl Sci 51 (2004) 3172-3177.
14. M.F. Bernard, L. Dusseau, S. Buchner, D. McMorrow, R. Ecoffet, J. Boch, J.R. Vaille, R.D. Schrimpf, K. LaBel, Impact of total ionizing dose on the analog single event transient sensitivity of a linear bipolar integrated circuit, IEEE T Nucl Sci 54 (2007) 2534-2540.
15. J. Beaucour, T. Carribre, A. Gach, P. Poirot, Total dose effects on negative voltage regulator. IEEE T Nucl Sci 41 (1994) 2420-2426.
16. R.L. Pease, S. McClure, J. Gorelick, S.C. Witczak, Enhanced low-dose-rate sensitivity of a low-dropout voltage regulator, IEEE T Nucl Sci 45 (1998) 2571-2576.
17. P. C. Adell, R. D. Schrimpf, W. T. Holman, J. L. Todd, S. Caveriviere, R. R. Cizmarik, K. F. Galloway, Total dose effects in a linear voltage regulator, IEEE T Nucl Sci 51 (2004) 3816-3821.
18. E. W. Enlow, R. L. Pease, W. E. Combs, R. D. Schrimpf, R. N. Nowlin, Response of advanced bipolar processes to ionizing radiation, IEEE T Nucl Sci 38 (1991) 1342-1349.
19. R.L. Pease, D.G. Platteter, G.W. Dunham, J.E. Seiler, H.J. Barnaby, R.D. Schrimpf, M.R. Shaneyfelt, M.C. Maher, R.N. Nowlin, Characterization of enhanced low dose rate sensitivity (ELDRS) effect using gated lateral pnp transistor structure, IEEE T Nucl Sci 51 (2004) 3773-3780.
20. M.F. Bernard, L. Dusseau, J. Boch, J.R. Vaille, F. Saigne, R.D. Schrimpf, E. Lorfevre, J.P. David, Analysis of bias effects on the total-dose response of a bipolar voltage comparator, IEEE T Nucl Sci 53 (2006) 3232-3236.
21. D. Chen, R. Pease, K. Kruckmeyer, J. Forney, A. Phan, M. Carts, S. Cox, S. Burns, R. Albarian, B. Holcombe, B. Little, J. Salzman, G. Chaumont, H. Duperray, A. Ouellet, S. Buchner, K. LaBell, Enhanced low dose rate sensitivity at ultra-low dose rates, IEEE T Nucl Sci 58 (2011) 2983-2990.
22. A.T. Kelly, P.C. Adell, A.F. Witulski, W.T. Holman, R.D. Schrimpf, V. Pouget, Total dose and single event transients in linear voltage regulators, IEEE T Nucl Sci 54 (2007) 1327-1334.
23. V. Ramachandran, B. Narasimham, D.M. Fleetwood, R.D. Schrimpf, W.T. Holman, A.F. Witulski, R.L. Pease, G.W. Dunham, J.E. Seiler, D.G. Platteter, Modeling total-dose effects for a low-dropout voltage regulator, IEEE T Nucl Sci 53 (2006) 3223-3231.
24. V. Vukić, P. Osmokrović, Radiation induced change of serial pnp power transistor's dropout voltage in voltage regulators, *Proceedings of the PIERS 2012*, Kuala Lumpur, Malaysia, March 27-30 (2012) 1180-1184.

25. V. Vukić, Minimum dropout voltage on a serial pnp transistor of a moderately loaded voltage regulator in a gamma radiation field, Nucl Technol Radiat 27 (2012) 333-340.
26. V. Vukić, P. Osmokrović, Impact of forward emitter current gain and geometry of pnp power transistors on radiation tolerance of voltage regulators, Nucl Technol Radiat 25 (2010) 179-185.
27. V. Vukić, P. Osmokrović, Total ionizing dose response of commercial process for synthesis of linear bipolar integrated circuits, J Optoel Adv Mater 8 (2006) 1538-1544.
28. ***, L4940 Series - very low dropout 1.5A regulators, STMicroelectronics, 2003.
29. V. Vukić, P. Osmokrović, On-line monitoring of base current and forward emitter current gain of voltage regulator's serial pnp transistor in radiation environment, Nucl Technol Radiat 27 (2012) 152-164.
30. M. Vujisić, K. Stanković, P. Osmokrović, A statistical analysis of measurement results obtained from nonlinear physical laws, Appl Math Model 35 (2011) 3128-3135.
31. A. Vasić, M. Zdravković, M. Vujisić, K. Stanković, P. Osmokrović, Temperature dependence of solar cell characteristics through frequency noise level and ideality factor measurements, Inform MIDEM 42 (2012) 98-103.
32. R. Gariboldi, M. Morelli, Very-low-drop voltage regulator with a fully complementary power process, IEEE J Solid-St Circ 22 (1987) 447–450.
33. R.L. Pease, G.W. Dunham, J.E. Seiler, Total dose and dose-rate response of low-dropout voltage regulator, IEEE Rad Eff Dat Wor (2006) 85-93.
34. F. Bertotti, C. Cini, C. Contiero, P. Galbiati, Monolithically integrated semiconductor device containing bipolar junction transistors, CMOS and DMOS transistors and low leakage diodes and a method for its fabrication, United States Patent 4887142, Dec. 12 (1989).
35. A. Holmes-Siedle, L. Adams, Handbook of Radiation Effects, Oxford University Press (2004).
36. P. Gray, P. Hurst, S. Lewis, R. Mayer, Analysis and Design of Analog Integrated Circuits, J. Wiley & Sons (2001).
37. G.C. Messenger, M.S. Ash, The Effects of Radiation on Electronic Systems, Van Nostrand Reinhold (1992).
38. R.F. Pierret, Semiconductor Device Fundamentals, Addison-Wesley (1996).
39. A. Wu, R.D. Schrimpf, H.J. Barnaby, D.M. Fleetwood, R.L. Pease, S.L. Kosier, Radiation-Induced Gain Degradation in Lateral PNP BJTs with Lightly and Heavily Doped Emitters, IEEE T Nucl Sci 44 (1997) 1914-1921.
40. S.S. McClure, J.L. Gorelick, R.L. Pease, B.G. Rax, R.L. Ladbury, Total dose performance of radiation hardened voltage regulators and references, IEEE Rad Eff Dat Wor (2001) 1-5.

Arrived: 11. 12. 2012
Accepted: 07. 02. 2013