IMPACT OF FORWARD EMITTER CURRENT GAIN AND GEOMETRY OF PNP POWER TRANSISTORS ON RADIATION TOLERANCE OF VOLTAGE REGULATORS

by

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Low-dropout voltage regulators with various geometries and technological realisations of serial pnp power transistors were exposed to ionizing radiation. Although devices with vertical emitters were considered much less susceptible to the influence of radiation on forward emitter current gain than circuits with round emitters, the experiment showed a similar degradation of current gain in both cases. The main reason of high radiation susceptibility of the examined vertical serial pnp transistor is the implementation of an interdigitated emitter, with high perimeter-to-area ratio, causing the great increase of serial transistor's base current, but a minor influence on the maximum output current. Transistors with round emitters with small perimeter-to-area ratio expressed a moderate current gain degradation, but a rapid fall of the emitter injection efficiency, causing a significant decrease of the maximum output current. Regardless of the similar forward emitter current gain degradation, reliability and operational characteristics of two types of low-dropout voltage regulators were completely different.

Key words: forward emitter current gain, power pnp transistor, lateral transistor, vertical transistor, voltage regulator, gamma radiation, quiescent current

INTRODUCTION

In the previous papers were presented the results of examinations of low-dropout voltage regulators "National Semiconductor" LM2940CT5 and "STMicroelectronics" L4940V5 in ionizing radiation fields [1-3]. It was perceived that voltage regulators LM2940CT5, manufactured by the use of a conventional monolithic bipolar process with lateral pnp transistors with round emitters, became unfunctional after the absorption of low doses of radiation – less than 300 Gy (SiO_2). On the other hand, voltage regulators L4940V5, BiCMOS integrated circuits created with implementation of local oxide side isolation process, showed much higher radiation hardness – more than 10 kGy (SiO_2). The hypothesis was that the main cause of L4940V5's high radiation hardness was small degradation of the serial vertical pnp transistor's forward emitter current gain (β), mainly due to the shift of the current flow from the surface towards the substrate, while the assumption of LM2940CT5's low radiation hardness was that it was caused by a rapid loss of lateral pnp transistor's forward emitter current gain in an ionizing radiation field.

For the precise answer on a change of the forward emitter current gain of voltage regulator's pnp power transistor in a radiation environment, beside the measurement of voltage regulator's output current, that is the serial transistor's collector current (i_C), it was necessary to procure the data of its base current (i_B). The quotient of these two currents represents a forward emitter current gain of a serial transistor. Yet, direct measurement of a base current in a voltage regulator was not possible without the unsealing of an integrated circuit (IC). Even if an IC was unclosed, it was not possible to perform the on-line measurements of a base current in a gamma radiation field, since the measuring equipment had to be introduced in a radiation field or the additional new connections had to be inserted, which would be mechanically and electrically very sensitive.

That was the reason why a novel method for the measurement of serial transistor's base current and forward emitter current gain had to be devised.

THEORY

The forward emitter current gain in a bipolar transistor is defined by the equation [4]

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$$\beta \quad \frac{\partial I_{\mathrm{C}}}{\partial I_{\mathrm{B}}} \quad \frac{I_{\mathrm{C}}}{I_{\mathrm{C}}} \tag{1}$$

Due to the lower common emitter current gain and the lower operating frequency, pnp transistors are more sensitive to ionizing radiation exposure than npn transistors [4]. Owing to the surface recombination mechanism, the influence of ionizing radiation is more expressed with lateral transistors, having the current flow right under the oxide layer, compared with vertical substrate transistors, where the current flows through the semiconductor bulk [5]. The main reason for the high radiation hardness of a vertical pnp transistor is a high implantation of the emitter p-type region, as well as evasion of a current flow in the proximity of the oxide surface [5]. Consequently, the spreading of the n-type base in the highly implanted p-type emitter region is weaker expressed in comparison with a vertical npn transistor, having the poorly implanted p-type base, causing the depletion region spreading on the base – the emitter junction of a vertical npn transistor. According to the results published in literature, the total dose necessary to reduce the forward emitter current gain of a vertical pnp transistor to 50% of its initial value may be up to 50 times higher than in the case of the lateral pnp transistor [6]. Beside an increase in the excess base current, in lateral pnp transistors a slight decrease in the collector current also contributes to the current gain degradation. The collector current changes significantly with the total dose. Since the base current increases at low total doses, reduction of a collector current has a strong impact on the current gain degradation. Two effects cause the decrease of collector current in the heavily doped emitter devices: the recombination in the neutral base region and the reduction of the emitter injection efficiency [7].

EXPERIMENT

Integrated 5-volt positive commercial-off-the-shelf voltage regulators "ST Microelectronics" L4940V5 and "National Semiconductor" LM2940CT5 were tested in the Vinča Institute of Nuclear Sciences, Belgrade, in Metrology – dosimetric laboratory.

As a source of γ-radiation the ^{60}Co was used and it was situated in a device for the realization of γ-field, IRPIK-B. The accepted mean energy of γ-photons was E_γ = 1.25 MeV. The samples were irradiated in the mouth of the collimator.

The exposition dose measurement was exerted with the cavity ionizing chamber "Dosimentor" PTW M23361, of the volume of $3\ 10^{-5}$ m^3, with the uncertainty of measurement of 2%. With the cavity ionizing chamber, the reader DI4 was used [8].

The samples of the voltage regulators LM2940CT5 and L4940V5 were irradiated in groups of four circuits. Ten meter long cables supplied the devices. Beside the supply cables, sense cables of the same length were laid. The 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 the detection of voltage regulator's degradation due to the exposure to ionizing radiation were forward emitter current gain and maximum load current. The measured electrical values were voltage regulator's output current, output voltage, and quiescent current, with the possibility to calculate the serial pnp transistor's forward emitter current gain.

In the low-dropout voltage regulators with the serial pnp transistor, quiescent current represents a sum of internal chip's supply current and serial transistor's base current. Subtracting a value of unloaded circuit's quiescent current from a loaded device's current, it is possible to calculate the serial transistor's base current. This method is not applicable on positive voltage regulators with serial npn transistor, since the base currents adds to the collector current, creating the emitter current, without any impact on the integrated circuit's quiescent current. Also, a relatively small value of the pnp transistor's forward emitter current gain is the cause of a relatively high base and, consequently, quiescent current, which can be measured precisely with the ordinary laboratory equipment, especially due to the fact that serial transistors are made of the great number of parallel connected elementary transistors. All mentioned facts provide the possibility to perform simple measurements in irradiated devices and to calculate i_{B} and β of the serial transistor, without the need to perform direct measurements on a chip.

The examination of the maximum collector current change was performed in the following way: for the constant input voltage equal to 8 V, the load current was increased until the output voltage dropped to 4.7 V. Lower output voltages are unacceptable for a voltage regulator, since a device is beginning to shutdown [9]. The next step was the measurement of the output voltage and quiescent current for an unloaded voltage regulator, with the input voltage of 8 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. The measurement of a quiescent current for an unloaded voltage regulator (I_{Q0}) provides the value of internal consumption, with a minor influence of the serial transistor's base current. The subtraction of unloaded circuit's quiescent current from a quiescent current of the maximally loaded device, for the same input voltages, gives a value of the serial transistor's base current

$$I_{\mathrm{B}} \quad I_{\mathrm{Q}}\Big|_{(I_{\mathrm{C}} \quad I_{\max})} \quad I_{\mathrm{Q0}}\Big|_{(I_{\mathrm{C}} \quad 0)} \tag{2}$$

The additional measurement of an output current, *i. e.* serial power transistor's collector current, gives a possibility to calculate the forward emitter current gain of a serial transistor, both during the irradiation and after the absorption of a specified amount of the total dose.

The devices had been irradiated until the predetermined total doses were reached. To avoid the effects of recombination in the semiconductor after the irradiation, all measurements were performed up to half an hour after the exposure. The devices in the γ-radiation field were exposed to the total dose of 500 Gy, with the dose rate of 4 cGy/s.

More details about the experiment and technological processes implemented in the manufacturing of the examined circuits are provided in the references [2, 3].

RESULTS AND DISCUSSION

Data presented in figs. 1-5 were procured by the tests of circuits LM2940CT5 from batch PM44AE, made by "National Semiconductor's" subcontractor in China. The circuits were packaged in Malacca, Malaysia.

The very beggining of the irradiation of voltage regulators LM2940CT5 brought a rapid decrease of the maximum output current, but also the increase of the serial transistor's forward emitter current gain for the unbiased devices and circuits operating with low currents.

It was perceived earlier [1, 3] that the voltage regulators LM2940CT5 became unfunctional after the absorption of low doses of radiation. The main reason for circuit failures for the low total doses was not the loss of the forward emitter current gain, but the degradation of the error amplifier circuit [3].

Lateral pnp transistors are sensitive to the influence of ionizing radiation and in their radiation response dominate interface traps. Interface traps have

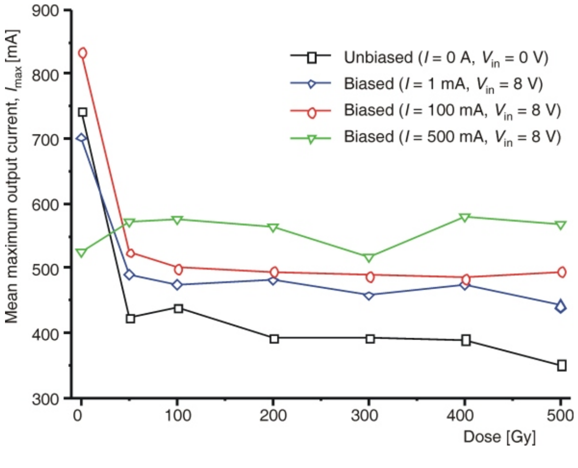

Figure 1. Change of mean maximum output current in voltage regulator LM2940CT5 under the influence of γ-radiation

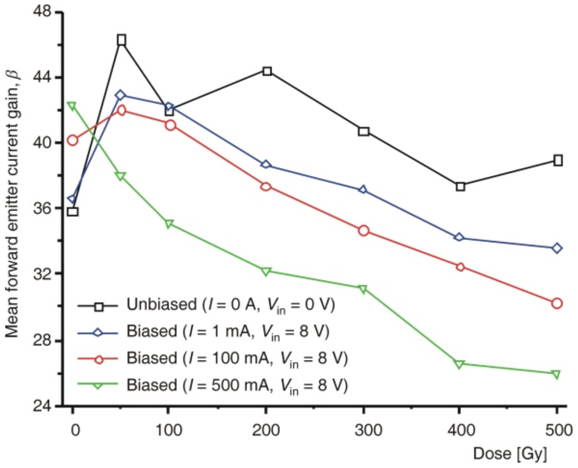

Figure 2. Change of mean serial transistor's forward emitter current gain in voltage regulator LM2940CT5 under the influence of γ-radiation

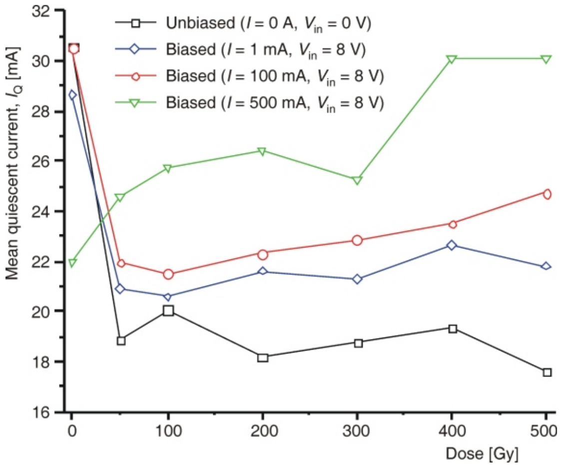

Figure 3. Change of mean quiescent current in voltage regulator LM2940CT5 under the influence of γ-radiation

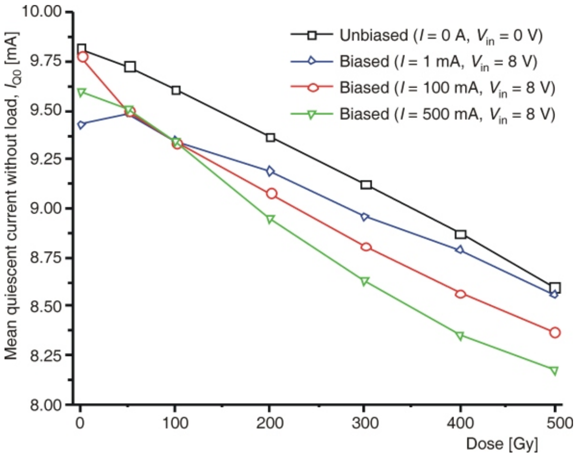

Figure 4. Change of mean quiescent current in unloaded voltage regulator LM2940CT5 under the influence of γ-radiation

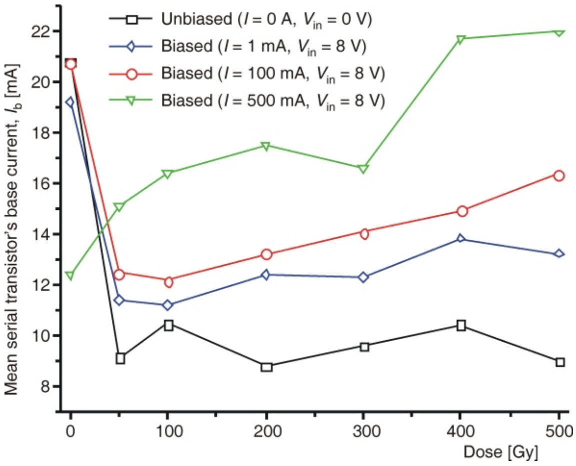

Figure 5. Change of mean serial transistor's base current in voltage regulator LM2940CT5 under the influence of γ-radiation

the primary influence on the spread of the depletion region on the base – the emitter junction and increase of base current. On the other hand, positive trapped charge in the oxide has an influence on the increase of the lateral pnp transistor's radiation hardness, causing the accumulation of the n-type base surface, suppressing the holes towards the substrate. Positive trapped charge in the oxide and interface traps above the p-type emitter area are additive, causing the great efficiency degradation of lightly doped emitters [7]. Therefore, the base current is also affected by the decrease of the emitter injection efficiency.

In the beggining of the irradiation of the voltage regulator LM2940CT5, due to the slow formation of interface traps, oxide traps had the dominat influence, causing the rapid increase of electric field generated by the positive trapped charge in the oxide. The electric field caused by the positive trapped charge rises quickly in the highly contaminated oxides [10-12]. Under the influence of the external electric field the transport of holes and hydrogen ions towards the interface oxide – semiconductor and the generation of interface traps starts. Owing to the influence of the "electrostatic barrier", generated by space charges in the oxide, the hole and hydrogen ion transport towards the interface was very slow, causing the dominant influence of oxide trapped charge on the lateral pnp transistor. This effect induced the abrupt reduction of the emitter efficiency and the decrease of the base current due to the reduction of the space-charge region in the base area [8]. The increase of the absorbed total dose caused higher electron injection from the base into the emitter area, but also the lateral pnp transistor's base width modulation, set up by the hole supression towards the substrate. Both mechanisms had the impact on the increase of the base current during the irradiation.

The specified interpretation relates to the operation with small emitter currents. When the high current flows through the emitter, due to the degradation of lightly doped emitter, caused by the positive trapped charge in the oxide, the space-charge region spreads deep into the p-type emitter. The examined samples with the load current of 500 mA operate with the significantly lower forward emitter current gain, with the high carrier injection into the emitter. In the case of lateral pnp transistors, high holes current flows through the n-type base, suppressing the influence of positive trapped charge in the oxide on surface accumulation in the base area. The increase of the interface trap concentration proportional to the total dose causes the additional rise of the base current and the degradation of the forward emitter current gain. High current flow through the lateral pnp transistors does not cause a significant recombination of positive trapped charge in the oxide because minority carriers in the pnp transistor's base area are holes.

Forward emitter current gain degradation of the serial pnp transistor is less than expected for lateral pnp transistors with lightly doped emitters (decrease up to 40% in regard to the current gain before the irradiation). Anyhow, it appeared that the older technological process, based on round, not interdigitated emitters, was the primary reason for the moderate degradation of the forward emitter current gain of the power transistor. On the other hand, small perimeter-to-area ratio had significant effect on degradation of the emitter injection efficiency, especially during the operation with high currents, reducing the maximum current supplied to the load. The small area of junctions base – emitter influenced a small spread of space-charge regions, *i. e.*, prevented the great increase of base current, having the forward emitter current gain values acceptable even after the absorption of the total doses of 500 Gy (SiO_2). Therefore, the information on forward emitter current gain in the operating point was not sufficient for the evaluation of serial transistor's radiation hardness, demanding also the information on maximum current.

Data shown in fig. 5 are good illustration of a dominant influence of the oxide trapped charge on the reduction of the base current. The most significant decrease of the base current can be seen in the unbiased samples, less in the biased circuits with the current of 1 mA, and the least decrease of serial pnp transistor's base current for the low-current samples is in the case of voltage regulators with the current of 100 mA. The increase of both input voltage and emitter current reduced influence of the oxide trapped charge, having an impact on the base width modulation and the partial annealing of oxide traps.

Opposite to the change of power transistor base current and, partly, output current, is a steady decrease of the integrated circuit's supply current, I_{Q0} (a quiescent current reduced for the value of the serial transistor's base current, fig. 4). The reduction of the supply current showed little dependence on the bias conditions and output current, indicating a permanent decrease of elementary low power transistor's forward emitter current gain and emitter injection efficiency.

In figs. 6-10 are presented data of examinations procured for voltage regulators "STMicroelectronics" L4940V5 from the batch WKOOGO 408, made in China.

Despite the verified great radiation hardness of voltage regulators L4940V5, from the fig. 7 can be noticed a significant decrease of the forward emitter current gain, reaching more than 50% in regard with the initial values. During the first series of experiments, it was assumed that the main reason for high radiation tolerance of voltage regulators L4940V5 was a small influence of ionizing radiation on the vertical pnp transistor's forward emitter current gain.

The main reason why the radiation susceptibility of the examined vertical serial pnp transistor was higher than expected is the implementation of the interdigitated emitter, with high perimeter-to-area ra-

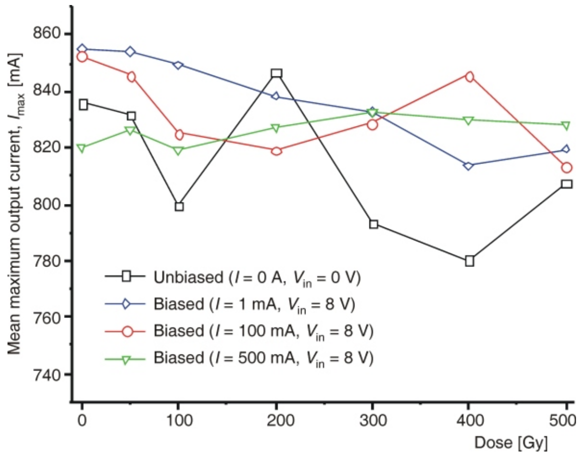

Figure 6. Change of mean maximum output current in voltage regulator L4940V5 under the influence of γ-radiation

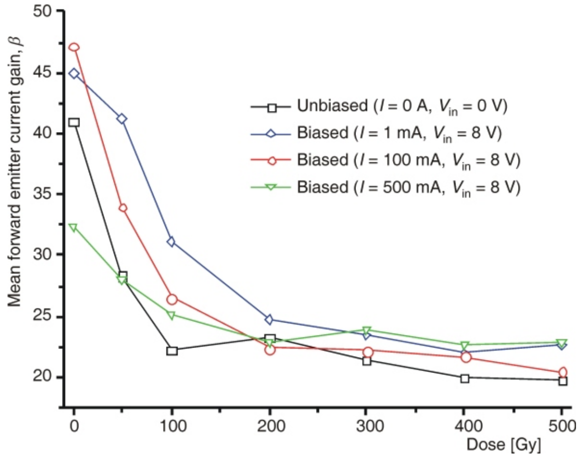

Figure 7. Change of mean serial transistor's forward emitter current gain in voltage regulator L4940V5 under the influence of γ-radiation

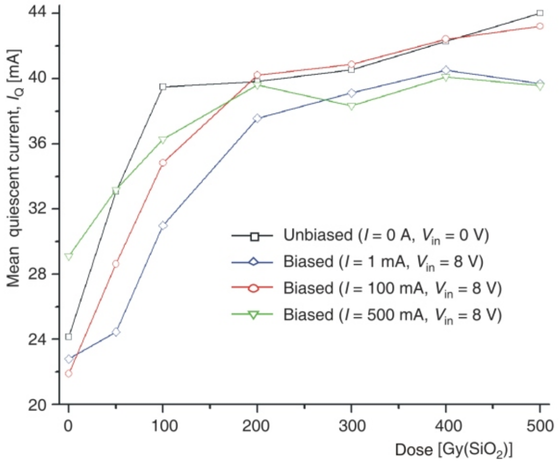

Figure 8. Change of mean quiescent current in voltage regulator L4940V5 under the influence of γ-radiation

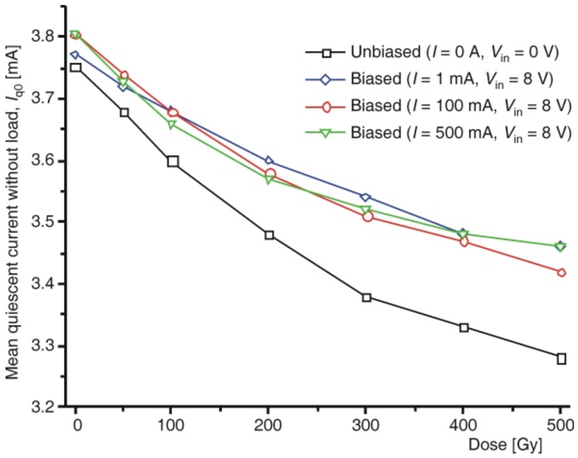

Figure 9. Change of mean quiescent current in unloaded voltage regulator L4940V5 under the influence of γ-radiation

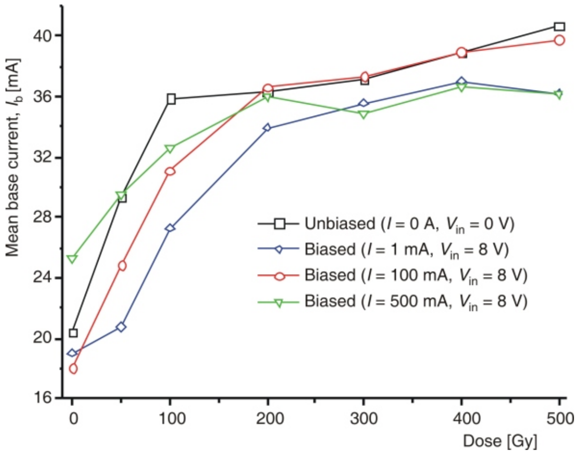

Figure 10. Change of mean serial transistor's base current in voltage regulator L4940V5 under the influence of γ-radiation

tio, applied in order to increase the emitter efficiency during the operation with high currents. In total, 36 groups of elementary pnp transistors occupy large chip area, with very high perimeter-to-area ratio [2]. Consequently, positive trapped charge in the oxide has the great impact on the emitter injection efficiency and a spread of space-charge region deep into the emitter area. After the initial rapid decrease, forward emitter current gain fell on a half of the initial value (for the samples with low load currents) after the absorption of the total dose of 200 Gy (SiO_2), remaining in the saturation for higher doses. Yet, for the exact evaluation of the forward emitter current gain degradation, the data on the serial transistor's base – emitter voltage (V_{BE}) are necessary. Although the base and emitter currents are known values, voltage V_{BE} during the measurement of the serial transistor's collector and base current remained unknown, since it was not possible to measure this value during the experiment. Only if the values of current gain were known in various conditions for the constant values of V_{BE}, the reconstruction of a characteristic $\beta(I_E)$ could be possible. Therefore, the conclusion is that owing to the negative feedback reaction the serial transistor's operating point moved away from the maximum of characteristic $\beta(I_E)$, and not for all values of emitter current twofold decrease of the forward emitter current gain appeared [8].

The examinations of the maximum output current (fig. 6) pointed to a small change of this parameter, although the forward emitter current gain was halfed in some cases. The examinations of the maximum output current demand serial transistor operation in the high level injection mode (ideality factor $n = 2$). In this mode a serial transistor operates in the far right part of the characteristic $\beta(V_{BE})$, where the change of V_{BE} has the least influence on forward emitter current gain. Some authors consider the reduction of a voltage regulator's maximum output current proportional to the serial transistor's forward emitter current gain [13], so a change of forward emitter current gain in the high-level injection mode of operation may be considered a base for a mutual comparison of sample's radiation tolerance. In the worst case, the decline of the maximum output current of the voltage regulator L4940V5 didn't exceed 7%. The increase of the base current, also as a stable regulation of the output voltage pointed to the primary significance of the driver transistor and control circuits (especially the voltage reference and error amplifier) on the voltage regulator's radiation hardness, while the current gain loss of the serial pnp transistor had less influence.

The mentioned effects did not have any influence on a proper functioning of circuit L4940V5, even after the absorption of very high total doses.

Similarities in radiation responses between two types of low-dropout voltage regulators were the characteristics of the samples that operated with high load currents during the irradiation and change of the voltage regulator's control circuit's supply current. In serial transistors operating in the conditions of the high-level carriers injection in the emitter (a total circuit's current of 500 mA), the noticed decline of lateral serial transistor's forward emitter current gain (voltage regulator LM2940CT5) was some 40%, while the current gain decline of the vertical transistor, situated in the circuit L4940V5, was about 30%. Voltage regulators L4940V5 showed the same trend of supply current decrease (fig. 9) as their counterparts with lateral transistors, but with a slightly more expressed decrease of unbiased samples supply current.

CONCLUSIONS

The implementation of a novel method for examination of low-dropout voltage regulator's characteristics in radiation environment gave the possibility to trace a change of base current and forward emitter current gain of a power pnp transistor in an integrated circuit without direct measurements on a chip. The voltage regulators "National Semiconductor" LM2940CT5, made by the use of conventional monolithic bipolar process with lateral pnp transistors and round emitters, showed the less degradation of the lateral pnp transistor's forward emitter current gain than expected. However, all samples had a functional failure after the exposure to low total doses of medium-dose-rate ionizing radiation. On the other hand, the voltage regulators "STMicroelectronics" L4940V5, BiCMOS integrated circuits created by the use of vertical process with side local oxides, confirmed high radiation hardness.

The increase of the absorbed total dose caused the higher electron injection from the base into the emitter area of lateral pnp transistors, but also the base width modulation, set up by the hole supression towards the substrate. Both mechanisms had an impact on the increase of the lateral pnp transistor's base current during the irradiation in voltage regulators LM2940CT5.

Detailed examinations of the voltage regulator L4940V5 pointed to the significant degradation of serial transistor's forward emitter current gain, that exerted by the great increase of voltage regulator's quiescent current. Nevertheless, this effect didn't affect device's proper functioning. The main reason for the noticed sensitivity of the examined vertical serial pnp transistor was the application of the interdigitated emitter, with the great perimeter-to-area ratio, used to increase the emitter injection efficiency.

The experiment pointed to the great influence of the emitter geometry on characteristics of a power transistor, comparable with the influence of the implemented technological process. Likewise, it was noticed that the changes of serial transistor's parameters did not need to be the decisive factor in the correct operation of integrated low-dropout voltage regulators in the radiation environment.

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УТИЦАЈ КОЕФИЦИЈЕНТА СТРУЈНОГ ПОЈАЧАЊА И ГЕОМЕТРИЈЕ ПНП ТРАНЗИСТОРА СНАГЕ НА РАДИЈАЦИОНУ ОТПОРНОСТ СТАБИЛИЗАТОРА НАПОНА

Стабилизатори напона направљени применом различитих технолошких поступака и геометријских распореда били су изложени јонизујућем зрачењу. Иако су транзистори са вертикалним емиторима сматрани мање осетљивим на утицај зрачења на коефицијент струјног појачања у односу на компоненте са латералним округлим емиторима, експеримент је указао на сличан ниво деградације струјног појачања у оба случаја. Основни разлог велике осетљивости испитиваних вертикалних серијских пнп транзистора је примена "тестерастих" емитора, са великим односом обим–површина. Због тога долази до великог повећања струје базе редног транзистора, али је утицај на максималну излазну струју био занемарљив. Стабилизатори напона са пнп транзисторима са округлим емиторима и малим односом обим–површина испољили су умерену деградацију коефицијента струјног појачања, али велики пад ефикасности емитора, утичући на значајно смањење максималне излазне струје. Без обзира на сличну деградацију коефицијента струјног појачања, поузданост и функционалност испитиваних стабилизатора напона биле су потпуно различите.

Кључне речи: коефицијенти струјног појачања, пнп транзистор снаге, латерални транзистор, вертикални транзистор, стабилизатор напона, гама зрачење, струја сопствене потрошње