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MINIMUM DROPOUT VOLTAGE ON A SERIAL PNP TRANSISTOR OF A MODERATELY LOADED VOLTAGE REGULATOR IN A GAMMA RADIATION FIELD

by

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The main examined value in an experiment performed on moderately loaded voltage regulators was the serial pnp transistor's minimum dropout voltage, followed by the data on the base current and forward emitter current gain. Minimum dropout voltage decreased by up to 12%, while the measured values of the forward emitter current gain decreased by 20-40% after the absorption of a total ionizing dose of 500 Gy. The oxide trapped charge increased the radiation tolerance of the serial lateral pnp transistor owing to the suppression of interface trap formation above the base area. Current flow through the serial transistor of the voltage regulator had an influence on the decrease in the power pnp transistor's forward emitter current gain. Due to the operation with a moderate load of 100 mA, loss of emitter injection efficiency was not as important as during the operation with high current density, thus eliminating the negative influence of emitter crowding on the radiation hardness of the voltage regulator. For a moderate load, gain in the negative feedback reaction was enough to keep output voltage in the anticipated range. Only information procured from tests of the minimum dropout voltage on the moderately loaded voltage regulators were not sufficient for unequivocal determination of the examined integrated circuit's radiation hardness.

Key words: minimum dropout voltage, forward emitter current gain, base current, lateral pnp transistor, voltage regulator, negative feedback loop, trapped charge, gamma radiation

INTRODUCTION

The response of voltage regulators in the radiation environment has been intensively examined in previous years, primarily due to their advantages over switching regulators: a simple electric circuit, low price, reduced noise and rapid transient response to load conditions [1]. Concern over the examination of voltage regulators particularly arose after the discovery of the enhanced low dose rate sensitivity (ELDRS) effect, leading to the analysis of numerous procedures anticipated for the procurement of precise information on the radiation tolerance of samples designed for service on satellites in the space radiation environment [1-14].

Results of the detailed examination of a low-dropout voltage regulator, the "National Semiconductor" LM2940CT5, in the gamma radiation field have been published previously [15-17]. The results on the change in the maximum output current and its influence on the serial transistor's forward emitter current gain were analysed two years ago [15]. Also, a new method has recently been proposed for on-line

monitoring of the serial transistor's forward emitter current gain in low-dropout voltage regulators, without interrupting the irradiation [16].

The foregoing results pointed out the low radiation tolerance of the conventional monolithic bipolar device, the "National Semiconductor" LM2940CT5, with round lateral pnp transistors [15-17]. However, the presented results relate to data of the maximum output current indicated in the high possibility of making an error in determining the device's radiation hardness based on experiments that only analyse a change of forward emitter current gain, particularly in electron devices with a negative feedback loop [16]. During the examination of the maximum output current, it was noticed that bias conditions had a great influence on the measured values of the forward emitter current gain [15]. Similar serial transistor forward emitter current gain degradation was perceived in the cases of lateral and vertical pnp power transistors in low-dropout voltage regulators, although BiCMOS voltage regulators with vertical pnp transistors demonstrated notable radiation hardness [15]. Also, even if the radiation tolerant low-dropout voltage regulator remains completely functional after irradiation, if its serial transis-

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tor's dropout voltage significantly increases, it may not be anymore suitable for the supply of battery powered devices or high-performance microprocessors, due to the notably increased dissipation or even decrease of output voltage below the acceptable limit.

In this paper the results related to the change in the serial transistor's minimum dropout voltage and forward emitter current gain in moderately loaded voltage regulators as a function of the absorbed total dose of gamma radiation, were presented.

THEORY

Low-dropout voltage regulators, linear integrated circuits with serial pnp power transistors, represent important elements in applications where a small difference between the input and output of power supply voltage is necessary. Application of low-dropout regulators in battery powered electronic devices enables longer autonomy, since the battery discharge process may take longer in comparison with standard voltage regulators having a serial npn Darlington transistor. The main reason is the serial transistor's dropout voltage, since the dropout voltage of a standard voltage regulator is approximately 2-2.5 V (sum of the collector-emitter voltage of a pnp driver transistor and base-emitter voltages of a Darlington configuration two elementary npn transistors). On the other hand, low-dropout voltage regulators usually have a voltage drop of nearly 0.5 V (only the collector-emitter voltage of the serial pnp transistor). Another important application is the power supply of high-performance microprocessors, with very high operating frequencies, high currents, and low operating voltages. Since these devices often operate with currents exceeding 10 A, a decrease in power dissipation in the microprocessor and its vicinity is imperative.

Dropout voltage of a voltage regulator with a serial pnp transistor is equal to the serial transistor's collector-emitter voltage. For a constant base current, an increase in collector-emitter voltage induces a decrease in the base width and, subsequently, an increase in the collector current I_C. The equation for the transistor collector current in the forward active region seeing the Early effect may be written as [18]

$$I_C \quad \frac{qAD_p n_i^2}{W_B N_D} \quad 1 \quad \frac{V_{CE}}{V_A} \quad \exp \frac{V_{BE}}{V_T} \qquad (1)$$

where, q is the charge of the electron, A – the cross-sectional area, D_p – the hole diffusion coefficient, W_B – the base width, N_D – the donor impurities concentration, V_{CE} – the collector-emitter voltage, V_A – the Early voltage, $V_T = kT/q$ – the thermal voltage, V_{BE} – the base-emitter voltage, k – the Boltzmann constant, and T – the temperature.

Since a linear voltage regulator is a feedback circuit, with error amplifier and negative feedback loop

on output voltage, a change in the serial transistor's collector-emitter voltage is a consequence of the combined influence of the physical effects on the elementary transistors and the negative feedback reaction. The magnitude of a bipolar amplifier's voltage gain is directly proportional to its quiescent DC current [18], while the low-dropout voltage regulator's total quiescent current represents the sum of the error amplifier's quiescent current, the serial transistor's base current, and the voltage divider's current. The general gain equation of a simple bipolar amplifier can be expressed as [1]

$$A_0 \quad g_m r_0 \quad \frac{I_C}{V_T} r_0 \qquad (2)$$

where, A_0 is the gain, g_m – the transconductance, and r_0 – the output resistance.

If the voltage regulator is unloaded, it can be assumed that the component of the serial transistor's base current in total quiescent current does not exist, that is, that the quiescent current of the voltage regulator is the sum of the control circuit's supply current and the voltage divider's current. Since the ionizing radiation has less influence on resistors than on bipolar transistors in an integrated circuit, for absorbed lower total doses it may be assumed that the ratio of the voltage divider is constant. Having the voltage regulator's output voltage and the voltage divider ratio, the supply current of the control circuit (in an unloaded voltage regulator) can be easily determined.

EXPERIMENT

An integrated 5-volt positive commercial off-the-shelf voltage regulator, LM2940CT5, was tested at the Vinča Institute of Nuclear Sciences, Belgrade, Serbia, in the Metrology-dosimetry laboratory.

The LM2940CT5 circuits were from the batch PM44AE, made by "National Semiconductor" subcontractor in China. The circuits were in plastic TO-220 cases, packaged in Malacca, Malaysia [15].

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

The measurement of the exposition doses was performed with the cavity ionizing chamber "Dosimentor" PTW M23361, with a volume of $3 \cdot 10^{-5}$ m^3. With the cavity ionizing chamber, the reader DI4 was used [16].

Devices were 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/s. The samples of the voltage regulators were supplied by flat cables 10 m long. Alongside the power supply cables, sense cables of the same

length were laid. To avoid the effects of recombination in semiconductors after irradiation, all measurements were performed within a time interval of half an hour after exposure.

Current and voltage measurements were carried out with laboratory instruments; a "Fluke" 8050 A and a "Hewlett-Packard" 3466A. Uncertainties of measurement for the specified instruments were 0.03% and 0.05%, respectively. All measurements and the irradiation of the components were performed at a room temperature of 20 °C. Measured effective value of noise in the sense cables was approximately 200 V. For the analysis of data obtained from four samples of voltage regulators LM2940CT5, the type A uncertainty of measurement was used. According to the guidelines found in literature [19, 20], calculated combined uncertainty of measurement for implemented experimental procedure was approximately 0.6%.

The principal quantities used for the detection of the voltage regulator's degradation due to exposure to ionizing radiation were the serial transistor's forward emitter current gain and collector-emitter (dropout) voltage. The measured electrical values were the voltage regulator's input and output voltages and quiescent current. The serial pnp transistor's forward emitter current gain was calculated under the assumption that the base current (I_B) of the serial pnp transistor in the voltage regulator can be found as the difference between the entire voltage regulator's quiescent current and the control circuit's internal consumption current [15, 16].

During irradiation, the examined biased devices were supplied with the same input voltage, 8 V, whilst the load currents had three different values: 1 mA, 100 mA, and 500 mA. The fourth group of irradiated devices were unbiased voltage regulators without an input supply voltage.

The examination of the change in minimum collector-emitter (dropout) voltage on the serial transistor was performed in the following way: input voltage was increased until output voltage dropped to 4.9 V, for a constant output current of 100 mA [17]. The difference between input and output voltage represents the dropout voltage on the serial transistor for the corresponding current.

The next step was the measurement of the output voltage and quiescent current for an unloaded voltage regulator, with input voltage equal to the value measured on the device loaded with 100 mA, as low as necessary to reduce output voltage to 4.9 V. In voltage regulators with a serial pnp power transistor, a quiescent current (I_Q) represents the sum of the control circuit's internal consumption current and the serial transistor's base current. Quiescent current of the unloaded voltage regulator (I_{Q0}), with a constant input voltage, was assumed to be approximate to the value of the loaded voltage regulator's internal consumption [15, 16]. Subtrac-

tion of the unloaded circuit's quiescent current from a quiescent current of devices loaded with 100 mA, for the same input voltages, gave a value of the serial transistor's base current [15, 16].

The serial transistor's forward emitter current gain was determined as a quotient of the voltage regulator's output current (i. e. the serial transistor's collector current on the resistor) and the calculated value of the base current.

A schematic circuit diagram of the voltage regulator LM2940CT5 is presented in fig. 1. Further details about the experiment, implemented technological process and construction of the lateral pnp transistor can be found in [15-17]. A detailed description of the LM2940CT5 integrated circuit is presented in [21].
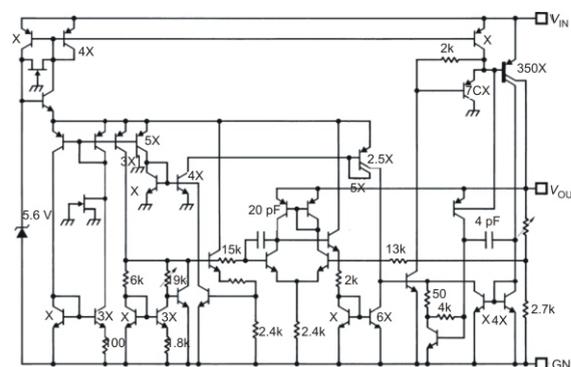
Figure 1. Circuit diagram of the voltage regulator "National Semiconductor " LM2940CT5 [16, 21]

RESULTS AND DISCUSSION

Figures 2-7 present changes in the serial transistor's dropout voltage, forward emitter current gain and base current for the "National Semiconductor" LM2940CT5 voltage regulators, for a constant load current of 100 mA and output voltage of 4.9 V. Although a rise in the minimum dropout voltage on the serial transistor associated with an increase in the absorbed total dose would be the expected effect, a slight decrease in dropout voltage may be observed (fig. 2). The serial transistor's base current has an ascending trend, regardless of the bias conditions, causing the steady decline in the serial transistor's forward emitter current gain, different from most of the observed trends during the examinations of the maximum output current [15, 17]. Opposite to the noticed sharp decline of the base current, after the absorption of very low total doses during the examinations of the maximum output current [15], whence the experiment on the change in the serial transistor's minimum dropout voltage were performed, similar effects were not perceived.

The explanation for the different responses was the negligibly lower influence of degradation of the

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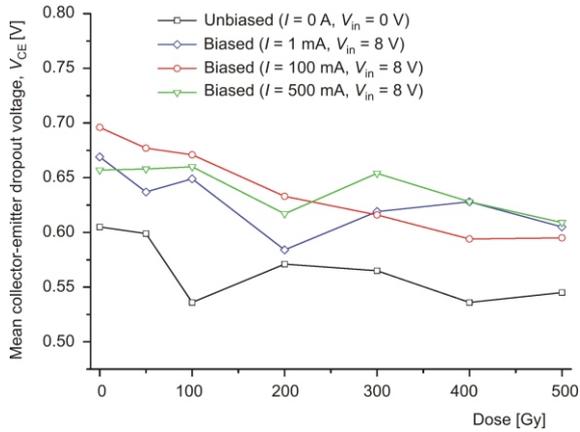
Figure 2. Change in the mean serial transistor's minimum dropout voltage in the voltage regulator LM2940CT5 under the influence of γ-radiation ($V_{out} = 4.9$ V, $I_{out} = 100$ mA)

Figure 3. Change in the mean serial transistor's forward emitter current gain in the voltage regulator LM2940CT5 under the influence of γ-radiation ($V_{out} = 4.9$ V, $I_{out} = 100$ mA)

Figure 4. Change in the mean serial transistor's current gain degradation in the voltage regulator LM2940CT5 under the influence of γ-radiation ($V_{out} = 4.9$ V, $I_{out} = 100$ mA)
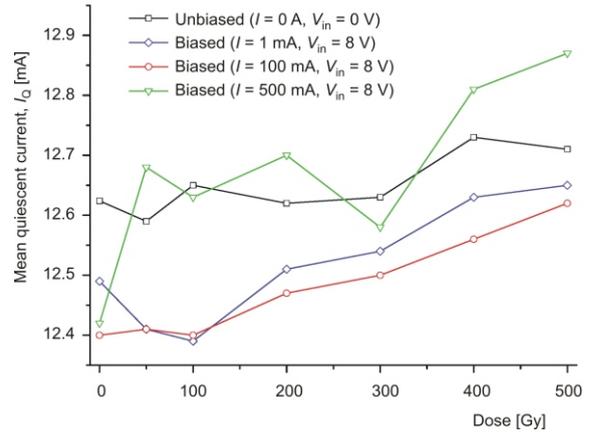
Figure 5. Change in the mean quiescent current in the voltage regulator LM2940CT5 under the influence of γ-radiation ($V_{out} = 4.9$ V, $I_{out} = 100$ mA)
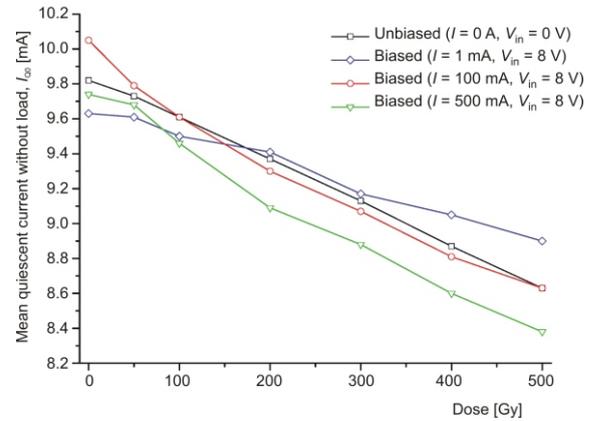
Figure 6. Change in the mean quiescent current in the unloaded voltage regulator LM2940CT5 under the influence of γ-radiation ($V_{in} = V_{CE(100 \, mA)} - 4.9$ V, $I_{out} = 0$ A)
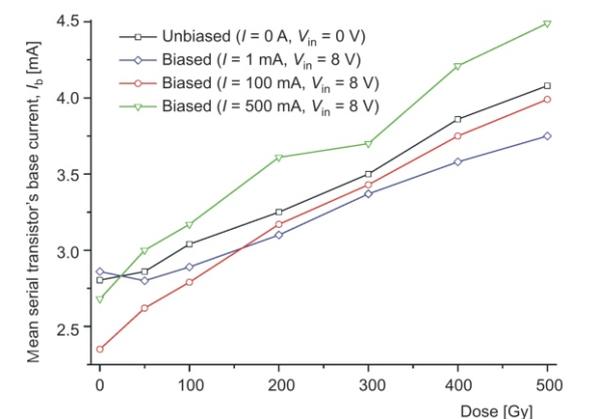
Figure 7. Change in the mean serial transistor's base current in the voltage regulator LM2940CT5 under the influence of γ-radiation ($V_{out} = 4.9$ V, $I_{out} = 100$ mA)

serial transistor's emitter injection efficiency during the operation with smaller serial transistor current densities (load current of 100 mA for 1 A device, in comparison with the load currents of 500-800 mA in

experiments related to the maximum output current [15, 17]).

As previously reported [15], degradation of the serial transistor's forward emitter current gain was less

than expected (up to 40% for a total ionizing dose of 500 Gy), and in the case of the experiment with low load current, degradation of the emitter injection efficiency of the elementary round lateral pnp transistors was not so important. The small perimeter-to-area ratio of the older technological process was, in this case, advantageous, having a small influence on the spreading of the depletion region in the emitter area on the serial transistor's base-emitter junction [17]. Thus, the oxide trapped charge above the emitter area had a smaller influence on the increase in the base current, causing the moderate degradation of the serial transistor's forward emitter current gain and also preservation of its acceptable characteristics after the absorption of a total ionizing dose of 500 Gy.

Compared with the data on forward emitter current gain obtained during the examination of maximum output current [15], only the results for the heavily loaded samples during irradiation (V_{in} = 8 V, I = 500 mA) had similar characteristics, while the other data pointed to different trends, as can be seen in figs. 3 and 4. In the case of examination of the dropout voltage of moderately loaded voltage regulators LM2940CT5, load and bias conditions did not lead to qualitative differences between characteristics of the serial transistor's forward emitter current gain and the base current.

Compared with the previously recorded results, the characteristics of the quiescent current show particularly interesting behaviour (fig. 5). These curves demonstrated only a slight increase, from 1% to 4%, with an absorbed total ionizing dose up to 500 Gy, without a sharp decrease in the lightly loaded and unloaded devices immediately after the start of irradiation, as in the case of the examination of the maximum output current [15]. On the contrary, the derived characteristics of the quiescent current procured from unloaded devices (internal consumption of integrated circuits, fig. 6) in two experiments showed very similar responses.

Data on the serial transistor's base currents pointed to crucial conditions causing the difference (fig. 7) . Examination of the serial transistor's dropout voltage was performed with a moderate current (100 mA), without the need for circuits to operate on boundaries of their limits. Therefore, during the experiment on the minimum dropout voltage, emitter crowding did not occur. Operation with high current densities during the examination of the voltage regulator's maximum output current [15] led to a clear perception of the reduction in emitter injection efficiency. Therefore, initial charge trapping immediately after the beginning of irradiation, causing the generation of a high concentration of the oxide trapped charge, did not have the same influence in cases of moderate and heavy loads. Moderately loaded voltage regulators operated with an output current of 100 mA and the serial transistor's base currents in the range 2.5-4.5 mA during examination of the minimum dropout voltage after irradiation. On the other hand, heavily loaded devices, during examinations of the maximum output current, operated with an output current of nearly 800 mA, with base currents in the range of 10-20 mA for one-ampere serial transistor [15]. Consequently, the influence of the initial charge trapping immediately after the beginning of irradiation was much less expressed during the examination of the minimum dropout voltage in circuits loaded with only 100 mA.

Immediately after the start of irradiation the generation of oxide and interface traps begins [22]. Accepted hypothesis is that an increase in the interface trap concentration (N_{it}) induces degradation of the lateral pnp transistor, while the rise in oxide trap concentration (N_{ot}) above the base area reduces the negative effect of the interface traps on the increase in a pnp transistor's base current, according to expression [23]

$$\Delta I_B \sim N_{it} \frac{1}{N_{ot}{}^2} \qquad (3)$$

Therefore, the conclusion may be drawn that due to the poor quality of the isolation oxide [17] high concentration of the trapped charge was accumulated above the serial transistor. Together with the positive bias voltage, oxide trapped charge suppresses the negative effect of interface traps and decreases the fall in the forward emitter current gain and base current. Also, as it was perceived earlier [17], the load regulation characteristic of the voltage regulator LM2940CT5 for a current of 100 mA was still satisfactory and a driver transistor of the error amplifier circuit had sufficient power to affect the serial transistor and obtain output voltage near the referent value of 5 V.

In total, the minimum dropout voltage of the lateral pnp transistor decreased by up to 12%, while the measured values of the serial transistor's forward emitter current gain in devices LM2940CT5 decreased by 20-40% after the absorption of a total ionizing dose of 500 Gy [24]. Yet, it has to be mentioned once again that acceptable radiation tolerance of the serial transistor comprising 350 elementary lateral pnp transistors [16, 17] was not enough to maintain the voltage regulator's radiation tolerance, since the circuit became inoperable after the malfunction of the voltage regulator's error amplifier circuit during operation with higher currents [17].

Nevertheless, some moderate differences related to the bias and load conditions existed between the examined devices. Since the voltage regulator LM2940CT5 is a monolithic integrated circuit with lateral pnp transistors, with lightly doped emitters [17], all basic mechanisms of the radiation effects observed in the pnp transistors (depletion of the p-type emitter, recombination at the base surface, enhanced electron injection into the emitter and surface hole depletion [25]) had influence on the characteristics of the examined devices.

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Since the emitter was not heavily implanted, mechanisms of electron injection into the emitter and surface hole depletion would also have significant influence on the serial transistor's forward emitter current gain. Enhanced electron injection into the emitter is manifested through the accumulation of the surface of the base, caused by the positive oxide charge trapped in the oxide over the emitter-base junction [25]. Forward bias of the base junction would cause many electrons to be injected into the emitter, thus increasing the base current.

The surface hole depletion mechanism is related to the path followed by the holes injected into the base. Since the holes are suppressed away from the isolation oxide, owing to the influence of radiation-induced oxide traps, hole paths in the base area becomes longer, leading to increased hole recombination in the base area and, therefore, an increase in the base current [25].

Due to the operation with moderate load, loss of the emitter injection efficiency was not important as in the case of operation with high current density. Another factor that would potentially lead to a secondary influence of emitter depletion is the absence of the interdigitated emitter in the voltage regulators LM2940CT5, additionally reducing the influence of the emitter depletion mechanism (caused by the mutual influence of radiation-induced interface traps and the oxide trapped charge above the emitter area) on radiation hardness of the voltage regulator. Therefore, although emitter depletion may be the most expressed degradation mechanism in a lateral pnp transistor with lightly doped emitters [26, 27], owing to the operation with a moderate load current and a relatively small emitter perimeter, this mechanism may have less influence than expected.

Recombination in the base surface was significantly suppressed by the trapped charge in the oxide above the base area, but results on the serial lateral pnp transistor's forward emitter current gain pointed to the high bias voltage and load current dependency of this mechanism (fig. 4). Both moderate and high load current (100 mA and 500 mA) during irradiation affected the serial transistor's current gain owing to the increased recombination of the oxide trapped charge above the base area, reducing the forward emitter current gain down to 60% of its initial value. Opposite to the moderately and heavily loaded devices, input bias voltage of 8 V on devices with negligible load current of 1 mA had significantly better influence on the serial transistor, preserving current gain at 80% of its initial value after absorption of a total ionizing dose of 500 Gy. This positive effect was fulfilled by the suppression of interface trap formation on the surface of the base area, due to the existence of an external electric field in the thick isolation oxide, caused by the input bias voltage. Between these two extremes were situated unbiased samples of voltage regulators LM2940CT5, without input bias voltage and load current.

Therefore, it may be deduced that current flow (during irradiation) in proximity to the isolation oxide in the voltage regulator LM2940CT5 had more influence on the decrease in the serial pnp transistor's current gain in comparison with the effect of the input positive bias voltage on the increase in current gain.

None of the examined samples of voltage regulators LM2940CT5 showed output voltage to fall bellow the threshold of 4.9 V during the examination of dropout voltage with a moderate load of 100 mA. However, heavily loaded devices during irradiation (load current was 500 mA) almost constantly operated with output voltage in the unacceptable range of 4.8-4.9 V [16].

CONCLUSIONS

Examination of the serial transistor's collector-emitter voltage in moderately loaded voltage regulators (100 mA for one-ampere devices) presented some new information on the change in the forward emitter current gain and base current. Regardless of the same bias conditions as in the experiment on the maximum output current, examination of dropout voltage with minimum input voltage and moderate load current brought some new insights into the radiation effects in bipolar voltage regulators.

Voltage regulators LM2940CT5 with lateral round pnp transistors demonstrated the dominant influence of an oxide trapped charge above the base area that decreased the rise in the serial pnp transistor's base current. A steady rise in the interface trap concentration during irradiation led to a rise in the base current of the lateral round pnp transistor by no more than 50-60% for a total dose of 500 Gy. In this case, the trapped charge in the isolation oxide did not cause the initial abrupt decrease in the base current and forward emitter current gain, as previously reported during the examination of the voltage regulator's maximum output current. The reason being the operation with a moderate load, preventing the manifestation of the emitter crowding in lateral pnp transistor with small perimeter-to-area ratio. Due to the examinations with a load of 100 mA, the gain in the negative feedback reaction was satisfying, keeping the output voltage near the referent value of 5 V (this was not the case in previous tests, where the voltage regulator LM2940CT5 showed notable radiation sensitivity, particularly for load currents of 300 mA and higher). However, interface traps and the oxide trapped charge have an additive effect on the emitter depletion, mutually causing the additional rise in the base current. Negative feedback reaction did not have influence on the serial lateral pnp transistor's base current comparable with the influence of the oxide trapped charge and interface traps.

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Dropout voltage decreased by nearly 10% during the irradiation of all examined samples. The total quiescent current of the integrated circuit was almost constant, but the unloaded device's quiescent current showed the same decreasing trend as noted during the examination of the maximum output current. Regardless of the bias condition, no significant differences were perceived in trends of the recorded characteristic in this series of experiments on voltage regulators LM2940CT5. Only data procured from tests of the minimum dropout voltage on moderately loaded voltage regulators LM2940CT5 were insufficient for unequivocal determination of the examined voltage regulator's radiation hardness.

ACKNOWLEDGEMENT

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МИНИМАЛНИ ПАД НАПОНА НА РЕДНОМ ПНП ТРАНЗИСТОРУ УМЕРЕНО ОПТЕРЕЋЕНОГ СТАБИЛИЗАТОРА НАПОНА У ПОЉУ ГАМА ЗРАЧЕЊА

Основна мерена вредност у експерименту спроведеном на умерено оптерећеном стабилизатору напона био је минимални пад напона на редном пнп транзистору, праћен подацима о струји базе и коефицијенту струјног појачања. Минимални пад напона смањио се за највише 12%, док су се мерене вредности коефицијента струјног појачања смањиле за 20%-40% након апсорбовања дозе јонизујућег транзистора сузбијањем формирања спојних захвата наелектрисања изнад области базе. Протицање струје кроз редни транзистор стабилизатора напона имало је утицај на смањење коефицијента струјног појачања пнп транзистора снаге. Због рада са умереним оптерећењем од 100 mA, пад ефикасности емитора није био значајан као у случају рада са великом густином струје, што је уклонило негативан утицај загушења емитора на радијациону отпорност стабилизатора напона. Током рада са умереним оптерећењем, појачање негативне повратне спреге је било довољно да одржи излазне параметре у предвиђеном опсегу. Подаци добијени током испитивања минималног пада напона на умерено оптерећеним стабилизаторима напона нису били довољни за недвосмислено утврђивање радијационе отпорности испитиваних интегрисаних кола.

Кључне речи: минимални пад напона, коефицијент струјног појачања, струја базе, латерални пнп транзистор, стабилизатор напона, негативна повратна спрега, захват наелектрисања, гама зрачење