POWER LATERAL PNP TRANSISTOR OPERATING WITH HIGH CURRENT DENSITY IN IRRADIATED VOLTAGE REGULATOR

by

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The operation of power lateral pnp transistors in gamma radiation field was examined by detection of the minimum dropout voltage on heavily loaded low-dropout voltage regulators LM2940CT5, clearly demonstrating their low radiation hardness, with unacceptably low values of output voltage and collector-emitter voltage volatility. In conjunction with previous results on base current and forward emitter current gain of serial transistors, it was possible to determine the positive influence of high load current on a slight improvement of voltage regulator LM2940CT5 radiation hardness. The high-current flow through the wide emitter aluminum contact of the serial transistor above the isolation oxide caused intensive annealing of the positive oxide-trapped charge, leading to decrease of the lateral pnp transistor's current gain, but also a more intensive recovery of the small-signal npn transistors in the control circuit. The high current density in the base area of the lateral pnp transistor immediately below the isolation oxide decreased the concentration of negative interface traps. Consequently, the positive influence of the reduced concentration of the oxide-trapped charge on the negative feedback reaction circuit, together with the favourable effect of reduced interface traps concentration, exceeded negative influence of the annealed oxide-trapped charge on the serial pnp transistor's forward emitter current gain.

Key words: forward emitter current gain, lateral pnp transistor, voltage regulator, current density, oxide-trapped charge, interface trap, gamma radiation, line regulation characteristic

INTRODUCTION

Low-dropout voltage regulators are widely used in analogue integrated circuits, being extensively implemented in modern nuclear technology and aerospace engineering [1-9]. Previously presented data on dropout voltage, base current and forward emitter current gain in moderately loaded voltage regulators has enabled new insights into the operation of these devices irradiated with minimum input voltage [10], somewhat different from the data procured from the examination of maximum output current, published several years ago [11]. But, one question on the radiation tolerance of the examined devices could not be answered only from the examination data of the dropout voltage of moderately loaded devices. Although the earlier examinations pointed to the low radiation hardness of voltage regulators LM2940CT5 with lateral round pnp power transistors [12], data on the serial transistor's dropout voltage and the derived characteristics obtained from examinations of moderately loaded devices were not enough to confirm the conclusions presented previously [10]. Also, the peculiar response of voltage regulators LM2940CT5 irradiated with high load current, which differed from all the other biased and unbiased samples, remained insufficiently clarified. How the high current density of the serial pnp transistor's emitter current exactly affected the operation of the voltage regulator LM2940CT5 remained ambiguous. So, beside the need to investigate if the change of dropout voltage on serial pnp transistors of the tested voltage regulators is really acceptable in the entire operating area, there is also a need to determine the elementary functional correctness of the examined devices in a radiation environment.

These arguments led to an examination of the dropout voltage of heavily loaded devices, with minimum operative input voltage and high output current.

This paper presents results related to the change of the serial transistor's dropout voltage and forward emitter current gain in heavily loaded voltage regulators as a function of the total absorbed gamma radiation dose.

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THEORY

In semiconductor devices, the ionising radiation damage is caused mainly by charges trapped near the surfaces of their insulating levels and interfaces. In junction devices, such as bipolar transistors, trapped charges in their surface layers produce inversion layers that expand the effective surface area. This results in increased surface state generation-recombination currents that reduce the lifetime of the minority carrier and, consequently, the current gain of bipolar transistors. These spurious currents have a special impact on the gain of bipolar transistors at low operating currents [13].

A device's susceptibility to radiation-induced charge production for a given dose depends strongly on its oxide layer quality. For bipolar transistors, the decreased current gain and increased leakage current are the two most important parameters degraded by ionising radiation. The principal factors that degrade performance due to ionising radiation are trapped positive charge build-up in their oxides near silicon surfaces, build-up of negative charge at Si-SiO$_2$ interfaces and the corresponding creation of surface states at these interfaces [13].

The surface recombination is the effect in bipolar transistors affected by ionising radiation that has the greatest influence on the degradation of the transistor's forward emitter current gain. For the bipolar transistor with circular emitter-base and base-collector junctions, an approximation of the change of the surface-recombination-affected current gain, β_S, can be presented in the following formula [13]

$$\frac{1}{\beta_S} \quad \frac{I_S}{I_E} \quad \frac{s2\pi R_e W^2}{D_b \pi R_e^2} \quad \frac{2s}{\frac{D_b}{W^2} \; R_e} \quad \frac{s(D_\gamma)}{\pi f_T R_e} \tag{1}$$

where, I_S is the surface recombination current, I_E – the emitter current, $D_b/W^2 = \omega_T = 2 \; f_T$, R_e – the emitter radius, W – the base width, D – the total ionising dose, s and $s(D\;)$ – the surface recombination velocity, D_b – the diffusion base constant, $A_e = \; R_e^2$ – the emitter area, f_T – the gain-bandwidth product (the cut-off frequency), and ω_T – the cut-off angular frequency.

Since the current gain degradation in a radiation environment, $\Delta(1/\beta)$, is proportional to the excess base current (ΔI_B) for not too large ΔI_B, the following equation may be written [13]

$$\Delta \; \frac{1}{\beta_s} \quad \frac{1}{\beta_s} \; \frac{1}{\beta_{s0}} \quad \frac{\Delta s(D_\gamma)}{\pi f_T R_e} \tag{2}$$

where, $\Delta s(D\;) = s(D\;) - s(0)$ is the change in the surface recombination velocity during the irradiation and β_{s0} – the surface-recombination-affected forward emitter current gain prior to irradiation.

In circular bipolar transistors, degradation of current gain caused by the surface recombination can be reduced by increasing the emitter radius. Nevertheless, bipolar power transistors are intentionally designed with maximally large emitter perimeter-to-area ratios, in order to reduce the base spreading resistance and, consequently, emitter crowding. Therefore, bipolar power transistors are extremely susceptible to common emitter current gain from ionising radiation [13].

The degradation of gain due to the ionising radiation is minimal at the collector current level corresponding to the maximum gain operating point prior to irradiation. For higher currents, the sensitivity to ionising radiation increases. For high-current density levels, an increase in the base current required to maintain constant collector current during irradiation leads to an effective increase in the base width because of the Kirk effect. The result is a direct expansion of the base-collector depletion region from the base into the collector, thus increasing the effective base width, and consequently leading to a decrease of the bipolar transistor's forward emitter current gain [14].

EXPERIMENT

An integrated 5-volt positive voltage regulator LM2940CT5 was tested at the Vinča Institute of Nuclear Sciences, Belgrade, Serbia, in the Metrology-dosimetric laboratory. The circuits LM2940CT5 were from the batch PM44AE, made by the National Semiconductor's subcontractor in China. 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 γ-field, IRPIK-B. The accepted mean energy of γ-photons is E = 1.25 MeV. The measurement of the exposure doses was performed with the cavity ionising chamber "Dosimentor" PTW M23361, with a volume of 3 10^{-5} m^3. With the cavity ionising chamber, the reader DI4 was used [11].

The devices were irradiated until the predetermined total doses were reached. The 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" 8050A and a "Hewlett-Packard" 3466A. Measurement uncertainties 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. For analysis of the data obtained from four samples of voltage regulators LM2940CT5, the type A measurement uncertainty was used. The calculated combined measurement uncertainty for the implemented experimental procedure was approximately 0.6% [10].

The principal quantities used for the detection of the voltage regulator's degradation due to exposure to ionising radiation were the serial transistor's forward emitter current gain and the 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 [10, 11, 15].

During the irradiation, the examined biased devices 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 were unbiased voltage regulators without an input supply voltage.

Examination of the change in the minimum collector-emitter (dropout) voltage on the serial transistor was performed in the following way: the input voltage was increased until the output voltage dropped to 4.9 V, for a constant output current of 400 mA. The difference between the input and output voltage represents the dropout voltage on the serial transistor for the corresponding current.

Owing to the decrease of the transistor's common emitter current gain after exposure to ionising radiation, the output voltage value tended to fall below 4.9V; therefore, in order to acquire complete data regarding the device's functioning ability after irradiation, it was also necessary to obtain the information about the change of the maximum output voltage as a function of the total ionising doze (TID). The next step was 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 400 mA, as low as necessary to reduce the 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. The quiescent current of the unloaded voltage regulator (I_{Q0}), with the constant input voltage, was assumed to be approximate 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 [10, 11, 15].

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.

All the mentioned measurements were performed in the incorporated experiments on voltage regulators, focused on the maximum output current [11], the minimum dropout voltage for moderately loaded devices [10] and, in this chapter on the study of commercial low-dropout voltage regulators LM2940CT5, the dropout voltage for heavily loaded samples. All three kinds of measurements were performed in the same conditions, in order specified in this paragraph. These results were obtained as a part of the second series of experiments performed on low-dropout voltage regulators in 2007.

Besides the examination of the minimum dropout voltage and related parameters, examination of the line regulation characteristics of the voltage regulators LM2940CT5 was also performed. In this experiment, the values of the output voltage were measured for constant output current (0 A, 100 mA, 300 mA, 500 mA, and 700 mA), while the input voltage had values of up to 15 V (specifically 6.5 V, 8 V, 10 V, 12 V, and 15 V) [12]. Five samples were used for each type of the voltage regulators LM2940CT5 examination. The resulting diagrams represent the difference between the 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 LM2940CT5, performed in 2005. Therefore, the ionising radiation dose rate differs slightly, having a value of 5.5 cGy(SiO_2)/s [12]. However, all the other measurement equipment, sources of radiation, dosimetry and experimental set-up were the same.

A schematic circuit diagram of the voltage regulator LM2940CT5 is presented in fig. 1. Further details about the experiment, the implemented technological process and construction of the lateral pnp transistor can be found in [10-12, 15-18]. A detailed

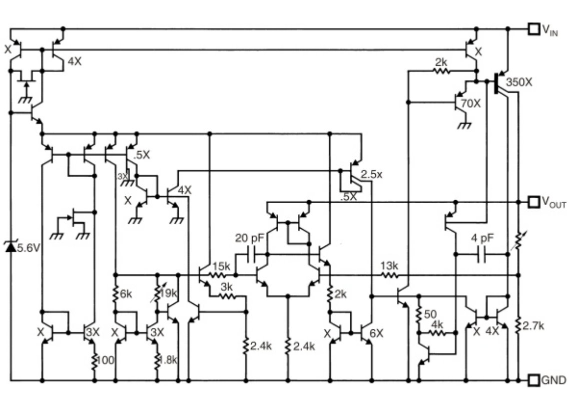

Figure 1. Circuit diagram of the voltage regulator "National Semiconductor" LM2940CT5 [10, 15, 19]

description of the LM2940CT5 integrated circuit is presented in [19].

RESULTS AND DISCUSSION

A few words are needed on the implemented technological process and characteristics of elementary pnp transistors in the voltage regulator LM2940CT5. The serial transistor is composed of 350 elementary lateral pnp transistors with a round emitter, connected in elementary groups of 18 and 24 elements [16]. The driver pnp transistor has 70 elementary pnp transistors, occupying 0.5 mm^2 of the voltage regulator's chip area, while the serial transistor comprising the 350 elements occupies 2.4 mm^2. Altogether, power pnp lateral transistors occupy approximately two thirds of the voltage regulator's chip [12, 16, 17].

Nominal parameters are $f_T = 2.5$ MHz, $BV_{CB0} = 94$ V [18], forward emitter current gain of the serial power transistor is $\beta = 24$ for $I = 1$ mA and $\beta = 15$-20 for $I_{max} = 1050$ mA [12, 16, 17]. The diameter of the round emitter of the elementary pnp transistor is 13 m. The thickness of the isolation silicon-oxide layer is 500 nm [17].

From the data on the collector-base plane breakdown voltage and an example from the literature ($N_C = 10^{15}$ cm^{-3} for $BV_{CE0} = 36$ V and $BV_{CB0} = 90$ V) [14], the concentration of impurities in the collector area may be estimated as nearly $N_C = 10^{15}$ cm^{-3}. From the data on the gain-bandwidth product, f_T, and the table for calculation of base width from approximate gain-bandwidth product in reference [20], the active base width in the lateral pnp transistor may be estimated as 12.6 m (slightly less than the emitter diameter). As can be seen from eq. (1), comprehension of the gain-bandwidth product, forward emitter current gain and emitter radius (for round lateral pnp transistors) may lead to estimation of the surface recombination velocity. Unfortunately, the parameter f_T is heavily dependent on the total absorbed dose of radiation, so precise calculation of the surface recombination velocity is not possible without calculating the gain-bandwidth product at every measurement point.

Examinations of voltage regulators LM2940CT5 with various load currents presented a somewhat different picture of the device's radiation hardness. If results were only obtained from examinations of the minimum dropout voltage with a load current of 100 mA, it might be wrongly concluded that the tested circuit is radiation tolerant for doses up to 500 Gy [10]. The older results would certainly contest this conclusion [11, 12, 15], but the radiation sensitivity of voltage regulators LM2940CT5 became obvious after examination of the minimum dropout voltage with higher load currents. From fig. 8 it is clear that none of the voltage regulators LM2940CT5 demonstrated acceptable radiation hardness sufficient to obtain an output voltage of at least 4.9 V, which is the lowest value for proper operation of the supplied 5 V electronic circuits. The decline in the output voltage below the acceptable limit was greatest for the unbiased devices, smaller for biased samples with negligible current and even smaller for biased devices with a moderate load current. The least degradation of the output voltage was demonstrated by heavily loaded biased devices irradiated with an input voltage of 8 V and load current of 500 mA. These heavily loaded devices demonstrated a minor decline in the output voltage at only one test point (fig. 8).

The data on output voltages are very important for proper interpretation of the serial transistor's dropout voltage characteristics in voltage regulators LM2940CT5. The dropout voltage characteristics, especially for unloaded and heavily loaded samples, are quite anomalous, often without any noticeable trend, as may be seen in fig. 2. The main reason is the operation with a proper voltage of 4.9 V at some test points, while at other points the maximum output voltage was between 4.7 V and 4.9 V (fig. 8). Efforts to procure proper results with the maximum available output voltage were not simple, since very intense recovery of the irradiated samples was observed during the measurements. Therefore, this effect led to the significant variations of the input voltage for maximum output voltages less than 4.9 V. This process was clearly expressed in all the voltage regulators LM2940CT5, particularly during the experiments with a high output current. Therefore, the change in dropout voltage in this experiment does not follow the trends of the previously recorded characteristics of moderately loaded devices [10].

The main reason is operation close to the limits of the output voltage and load current in a high-current density mode of the serial pnp transistor operation and, consequently, emitter crowding of the serial transistor. Therefore, emitter injection efficiency once again becomes an important parameter having the influence on the serial transistor's forward emitter current gain, by contrast with the tests with lower load currents, where

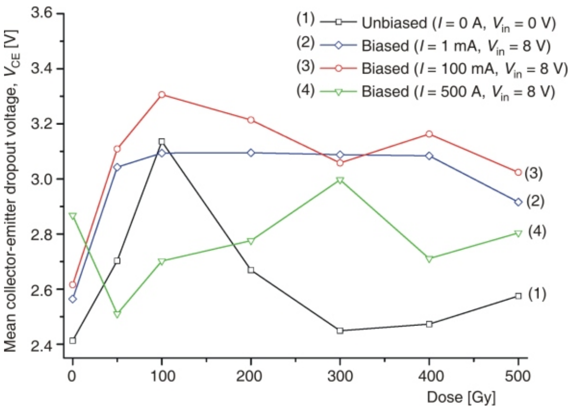

Figure 2. Change in the mean serial transistor's dropout voltage in voltage regulator LM2940CT5 under the influence of γ-radiation ($V_{out} = 4.9$ V, $I_{out} = 400$ mA)

the low perimeter-to-area ratio was not of great importance. Moreover, the negative feedback reaction and rapid recovery of the irradiated voltage regulators during the examinations with high currents additionally affected the serial transistor's dropout voltage.

The measured values of the serial transistor's forward emitter current gain (fig. 3) and current gain degradation (fig. 4) showed a similar decreasing trend to that noted during the examinations of the moderately loaded devices (the measured decrease of the forward emitter current gain was 30%-40%), but the absolute values of β were slightly higher than in all previous tests [10, 11], exceeding 50. Operation with greater values of current gain than in the cases of maximum and moderate loads led to the conclusion that the serial power transistors of the examined voltage regulators in this case operated near the maximum of characteristic $\beta(I_C)$.

Due to the considerable rise in the serial transistor's base current (by 3-5 mA), the total quiescent current (fig. 5) could not remain almost unaffected by irradiation, as was the case during the examination of the dropout voltage of the moderately loaded devices, where the increase of the base current was compensated by the decline in the integrated circuit's internal consumption current [10]. Similar descending trends in the measured values of forward emitter current gain in the moderately and heavily loaded devices necessarily led to similar increases in the serial transistor's base currents. The rise in the voltage regulators base currents examined with 400 mA was from 7.5-9 mA up to 11.5-13 mA (fig. 7), with the largest increase in the base current of the heavily loaded biased devices during irradiation (60%), and the smallest base current rise in the negligibly loaded biased devices (45%). As was expected, the characteristics of the internal circuit's consumption current were similar in both experiments (fig. 6).

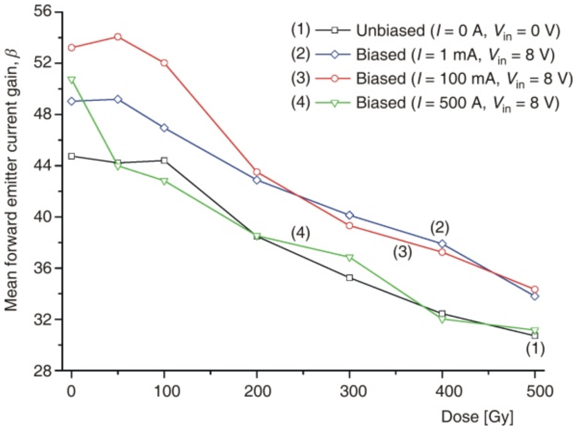

Figure 3. Change in the mean serial transistor's forward emitter current gain in the voltage regulator LM2940CT5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA)

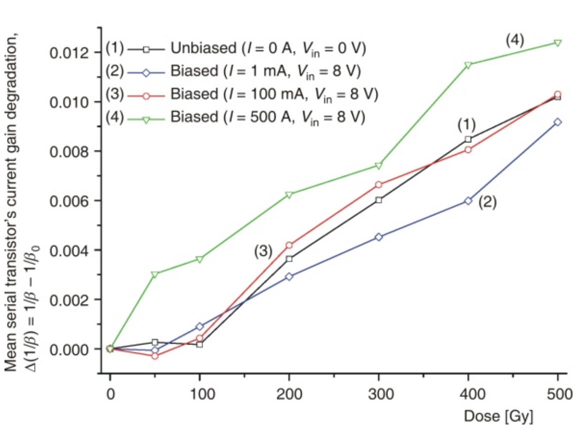

Figure 4. Change in the mean serial transistor's current gain degradation in the voltage regulator LM2940CT5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA)

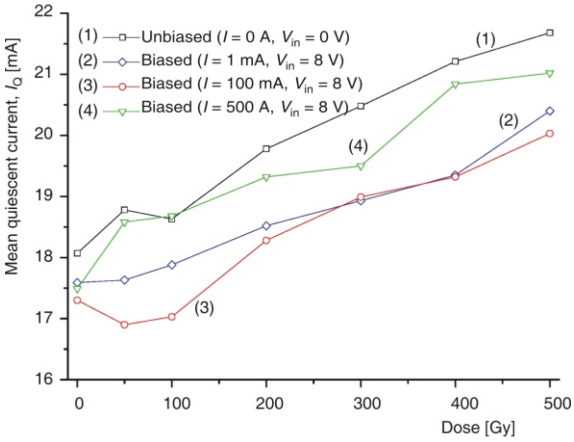

Figure 5. Change in the mean quiescent current in the voltage regulator LM2940CT5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA)

However, a very important difference is that during the examinations of dropout voltage with a load current of 100 mA, all samples remained functional, while during the tests of the same devices with a high load current of 400 mA, in all cases the output voltage fell below the threshold. The heavily loaded devices (bias condi-

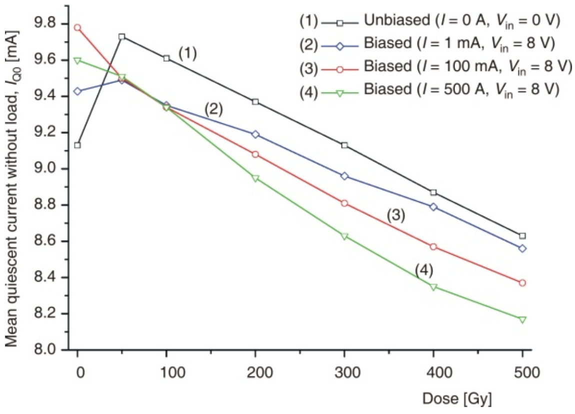

Figure 6. Change in the mean quiescent current in the voltage regulator LM2940CT5 under the influence of γ-radiation (V_{in} = $V_{CE(400\ mA)}$ + 4.9 V, I_{out} = 0 A)

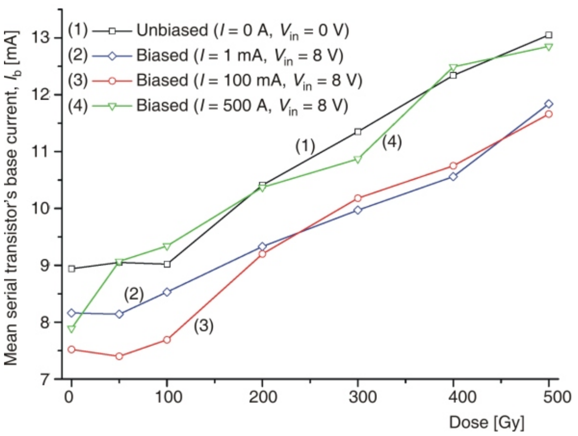

Figure 7. Change in the mean serial transistor's base current in the voltage regulator LM2940CT5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 400 mA)

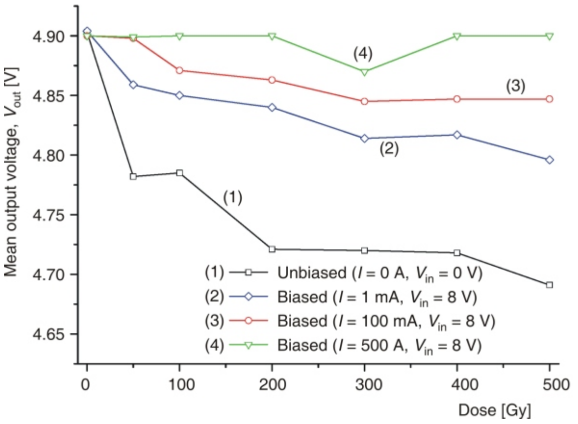

Figure 8. Change in the mean output voltage in the voltage regulator LM2940CT5 under the influence of γ-radiation ($V_{in} = V_{CE(400\ mA)} + V_{out}$, I_{out} = 400 mA)

tions: V_{in} = 8 V, I = 500 mA) mostly preserved an output voltage at the reference value of 4.9 V, but in the negligibly loaded and unbiased devices (V_{in} = 8 V, I = 1 mA) the output voltage fell below 4.9 V immediately after the beginning of irradiation.

We return now to the data on output voltage in fig. 8 and some comments have to be made on the results obtained. Unbiased bipolar devices with lateral pnp transistors are expected to show the greatest degradation of characteristics due to the greatest rise in the concentration of interface traps, as the main degradation mechanism of forward emitter current gain in lateral pnp transistors [21]. Since the existence of electric field in oxide suppresses the concentration of interface traps [22], it is clear that unbiased devices are more affected by interface traps. On the other hand, the trapped charge in the oxide above the lateral pnp transistors improves the radiation hardness of these transistors due to a decrease in recombination across the base-emitter junction, which consequently reduces the base current [23].

Since the isolation oxide of pnp transistors is very thick (approximately 500 nm, as already mentioned), a very high concentration of the oxide-trapped charge is expected, since the induced build-up of the oxide-trapped charge is higher in thicker oxides [24]. However, the positive effect of trapped charge in the oxide may be reduced if the lateral pnp transistor operates with high-current density, primarily due to a reduction of the emitter injection efficiency and the appearance of emitter crowding owing to the small perimeter-to-area ratio of the base-emitter junction. Therefore, a rise in the load current may affect both interface traps and the oxide trapped charge.

From figs. 4 and 7 it can be seen that the rise in the load current has a negative effect on the serial transistor's radiation hardness, contributing to an increase in degradation of the current gain and the base current of the power lateral pnp transistor. However, when the radiation tolerance of the complete voltage regulator was analysed, primarily on the ability of the negative feedback reaction to prevent the output voltage falling below the threshold of 4.9 V, the completely opposite situation could be seen. Regardless of the small differences in the increase of the base currents, the higher load currents during irradiation caused the output voltage to approach closer to the reference of 4.9 V (for a test load current of 400 mA after irradiation).

The radiation hardness of the voltage regulator's serial lateral pnp transistor rises as the ratio of the interface traps above the base area and the oxide-trapped charge concentrations (N_{it}/N_{ot}) decreases. Another important parameter for the radiation hardness of the complete voltage regulator is a gain of the negative feedback loop [8]. Moreover, the implemented bias voltage reduces the interface traps concentration in isolation oxide [25]. Finally, the current flow through the power lateral pnp transistor during irradiation also affects the trapped charge. Therefore, the characteristics of the output voltage cannot alone be used to determine the influence of load current on the voltage regulator's radiation hardness.

The influence of the serial transistor's current on the voltage regulators radiation tolerance, or in general, of the bipolar integrated circuits, has seldom been analysed in literature. In a study on the enhanced low-dose-rate sensitivity of low-dropout voltage regulators [2], Pease and co-workers noticed that operation of the voltage regulator 29372 with a moderate load current of 250 mA during irradiation significantly suppressed the total-dose damage. The authors concluded that mitigation of the damage was proportional to the load current and was not a strong function of temperature or input voltage during the irradiation. The mechanism for the mitigation of damage was identified as the current-density-dependent passivation of interface and border oxide traps by mobile hydrogen-related species, having the worst-case system application in unbiased samples [2]. The authors accepted a space charge model, having interface and border oxide traps composed of oxygen vacancy complexes, contributing to reduced surface recombination velocity [2]. These complexes may be passivated by various hydrogen-related species such as H, OH^-, and H^+ [2]. The high current density along the Si-SiO_2 interface may activate hydrogen-related species near the interface and cause passivation of the interface and border traps [2].

However, the useful information on the radiation response of the voltage regulators LM2940CT5 was procured also from previous examinations of the maximum output current (data on forward emitter current gain and base current, figs. 2 and 5 in reference [11]). In these diagrams, an explicit difference can be seen between the heavily loaded samples and all other devices during irradiation. The heavily loaded devices did not show an abrupt decrease in the base current or an initial rise in the forward emitter current gain. The announced interpretation [11] pointed to the dominant influence of the initial oxide-trapped charge in thick isolation oxide above the serial pnp transistor. In the case of heavily loaded devices, high-density current flow certainly had a considerable influence on the trapped charge and, indirectly, on the voltage regulator's radiation hardness.

The correlation previously noticed between the high load current (fig. 5 in reference [11]) and the rising trend of the base current [11], as well as the data on output voltage presented in this paper (fig. 8), led to the conclusion that high-density current flow through the serial pnp transistor and the isolation oxide during irradiation had a strong influence on recombination of the trapped charge. Reduction of the trapped charge may be interpreted as either a decrease of interface traps or concentration of oxide traps. Since the minority carriers in the *n*-type base area are holes, it is certain that the high concentration of holes in the base area led to passivation of some negative interface traps, thus increasing the radiation hardness of the serial pnp transistor, as mentioned in reference [2].

However, if other data on base current are analysed in the experiment on the maximum output current (fig. 5 in reference [11]), with unbiased and unloaded samples, the hypothesis on the influence of the high-current-density on the recombination of interface traps as a primary recovery mechanism for the voltage regulators LM2940CT5 is hardly tenable. The principal reason is the interface traps concentration increase during the irradiation. Also, in a weak electric field it was noticed that the rise in the interface traps concentration is proportional to the total ionising dose ($N_{it} \sim \quad D$) [26]. Thus, fast generation of interface traps that would affect a rapid decrease of base current in unbiased and moderately loaded devices (fig. 5 in reference [11]) was not possible. Therefore, after the initial period of irradiation, the main influence on the decrease of the serial transistor's base current originated from the abrupt rise in the oxide-trapped charge concentration, primarily affecting the base area owing to the decreased recombination in the base.

Consequently, it may be concluded that, in total, the concentration of the oxide-trapped charge in the voltage regulator LM2940CT5 significantly decreased due to the high-current-density flow in the proximity of the isolation oxide. Recombination of the oxide-trapped charge notably decreased its positive influence on the radiation hardness of the lateral pnp power transistor. But, on the other hand, oxide-trapped charge had a negative effect on npn transistors, so reduction of the oxide-trapped charge concentration increased the radiation hardness of a number of small-signal npn transistors in the control circuit of the voltage regulator LM2940CT5.

The mentioned article [11] published the conclusion that voltage regulators LM2940CT5 failed to operate reliably in a gamma radiation environment due to the significant degradation of the error amplifier circuit, regardless of the moderate degradation of the serial lateral pnp transistor. Firm confirmation of the well state of the voltage reference in the voltage regulator LM2940CT5 after absorption can be seen from the line regulation characteristics recorded during the first series of experiments on the voltage regulators LM2940CT5, after absorption of the total ionising dose of 300 Gy.

The first series of experiments on voltage regulators LM2940CT5 was also performed on the samples from the batch PM44AE, yet these devices were independent from those used to obtain the results presented in figs. 2-8. Both samples, which were unbiased and biased during the examination of the line regulation characteristics, were analysed after the absorption of a total gamma radiation dose of 300 Gy(SiO_2). Line regulation characteristics obtained without bias during the irradiation are presented in fig. 9, while fig. 10 shows 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. The data shown in figs. 9 and 10 point to minor

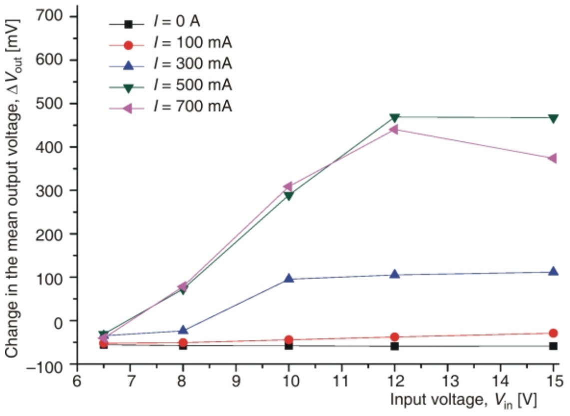

Figure 9. Relative line regulation characteristics of the unbiased voltage regulator LM2940CT5 after deposition of the total dose of γ-radiation of 300 Gy(SiO_2) (bias conditions: V_{in} = 0 V, I = 0 A)

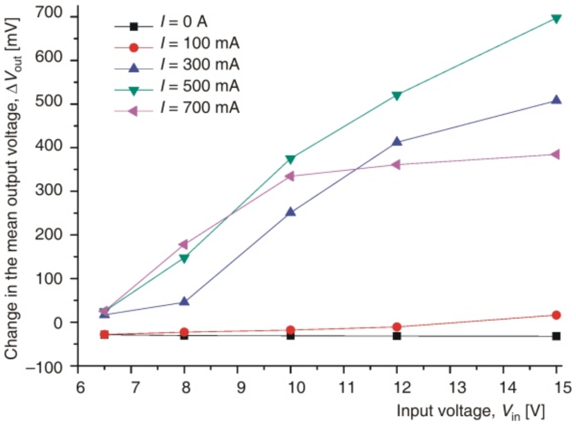

Figure 10. Relative line regulation characteristics of the biased voltage regulators LM2940CT5 after deposition of the total dose of γ-radiation of 300 Gy(SiO$_2$) (bias conditions: V_{in} = 7 V, I = 100 mA)

variations in the output voltage for load currents up to 100 mA, leading to the conclusion that the voltage reference remained relatively unaffected by the influence of gamma radiation. However, when the load current reached 300 mA and more, an unacceptable runaway from the referent voltage occurred. It can also be seen that the line regulation characteristics of the biased devices were more affected by the ionising radiation (decrease of the output voltage up to 700 mV from the pre-irradiation values (fig. 10), in comparison with approximately 500 mV (fig. 9) for unbiased devices). The data from figs. 9 and 10 regarding the line regulation characteristics for the load current of 700 mA are particularly interesting. In both cases there is a similar output voltage decline of 400 mV, but also a significant recovery is recorded for the maximum input voltage and high load current. As mentioned before, until the end of the nearly two-hour experiment on line regulation characteristics, the examined samples of voltage regulators LM2940CT5 significantly recovered, especially during the operation with high load currents. This was not the case with any other examined voltage regulators, such as the L4940V5 [27].

However, one important detail must be discussed. In the experiment on the maximum output current [11], it was concluded that the high current flow through the lateral pnp transistor could not lead to significant recombination of the trapped charge in isolation oxide above the transistor, since the minority carriers in the *n*-type base area are holes [11]. Protracted analysis of the radiation effects in low-dropout voltage regulators LM2940CT5 led to a conclusion on the reduced influence of the oxide-trapped charge caused by the device's operation with high current densities.

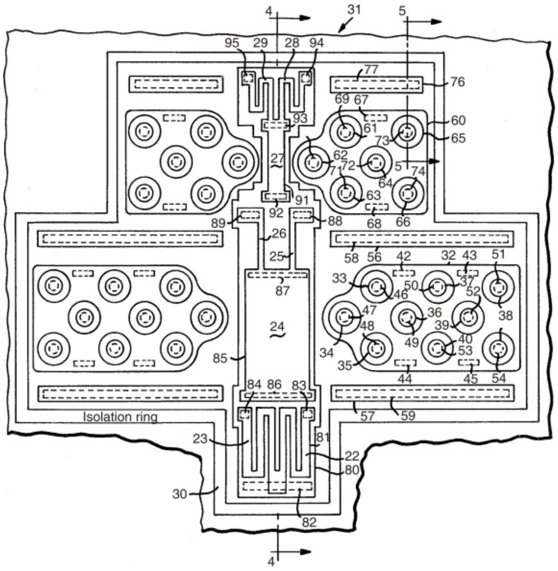

Figure 11. Topology of the lateral pnp power transistor [12, 15, 16]

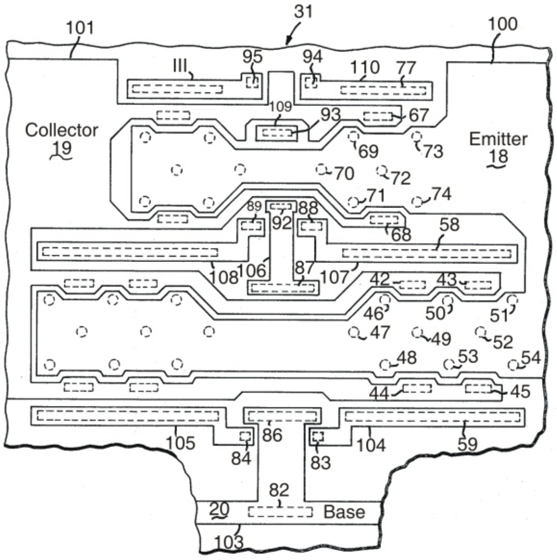

Figure 12. Metal contacts of the lateral pnp power transistor [12, 16]

Nevertheless, the solution to this dilemma came from an unexpected side. A careful analysis of the implemented technological process of lateral pnp power transistors with round emitters in voltage regulators (fig. 11) leads to an awareness of very large emitter aluminum contacts above the base, the emitter and even the collector areas of the power transistor, covering approximately half of the power transistor's surface (fig. 12). These large emitter metallizations are situated above the 500 nm isolation oxide. Therefore, it may be hypothesised that not the high-density hole current in the lateral pnp transistor, but rather the high-density electron current in the aluminum contacts had the decisive influence on the recombination of the oxide-trapped charge above the power transistor. Since the isolation oxide was highly contaminated, with a low dielectric loss factor [12], this assumption may be valid.

The simulations of basic physical mechanisms in semiconductors and insulators led to the hypothesis that the dominant influence on processes in transistors is that of the oxide charge (primarily holes) trapped up to 20 nm from the Si-SiO_2 interface [20]. On the other hand, in the transport processes of hydrogen ions, particles situated all over the oxide participate. Other effects are the external and internal electric field in the oxide, additionally contributing to the transport processes in the oxide. Therefore, the high-density current flow through the wide conductor above the low-quality insulator may lead to the intensive electron-trapping and recombination of a significant portion of the positive trapped charge in the oxide (holes and hydrogen ions).

It has to be repeated that this intensive oxide-trapped charge annealing was observed only during operation with very high currents and with current densities exceeding 1 A/mm^2. This situation is not expected in metal-oxide-semiconductor (MOS) transistors since their gate contacts are designed for operation above the insulating gate oxide, without input current, implying the absence of even minor current densities. Also, another factor that would prevent this effect in MOS devices is the higher oxide quality and its low thickness (d_{ox}). Isolation oxides in bipolar integrated circuits are of marginal interest, generally created by the deposition from a vapour phase and consequently leading to high oxide contamination [20]. On the other hand, MOS oxides are usually carefully grown in dilute dry oxygen [20], with great care in the reduction of impurities concentration in the gate oxide. Also, the thickness of MOS oxides is usually determined in tens of nanometers, not in hundreds of nanometers or even micrometers. Since the oxide-trapped charge concentration is a direct consequence of the oxide thickness (in bipolar oxides proportional up to d_{ox}^3) [20], the oxide-trapped charge would have a much higher influence in bipolar integrated circuits than in their MOS counterparts.

Therefore, regardless of the negative influence of high load current, affecting the serial transistor's forward emitter current gain and base current, high current density in the proximity of isolation oxide increased the radiation hardness of the voltage regulators LM2940CT5 owing to the partial recovery of small-signal npn transistors. Reduced npn transistors degradation improved the radiation hardness of the voltage regulator's control circuit.

After completion of irradiation, a brief isothermal annealing at room temperature was performed. This annealing, which lasted half an hour, did not lead clearly to a noticeable trend of recovery of the voltage regulator. However, following an examination of the irradiated integrated circuits, performed nearly five years later, it was found that the characteristics of the irradiated LM2940CT5 voltage regulators were similar to those prior to the irradiation. This result is completely in accordance with data on the annealing of LM2940CT5 devices obtained during the first series of experiments on voltage regulators in 2005. In this initial experiment on the minimum dropout voltage of LM2940CT5 voltage regulators, loaded with 400 mA during irradiation, it was noticed that exposed devices recovered almost to the initial values of the minimum dropout voltage after 168 hours of isothermal annealing at room temperature. Therefore, a greater annihilation of defects was expressed following the irradiation, than was the appearance of long-term degradation of LM2940CT5 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 knocks electrons off atoms in an insulator in order to create electron-hole pairs.

During the previous decade there have been several studies dedicated to the analysis of LM2941 adjustable low-dropout voltage regulators. These devices are essentially the same as LM2940CT5 voltage regulators but with one difference related to the state of the output voltage. While the LM2940CT5 voltage regulator is the fixed five-volt device, the LM2941 has an output voltage adjustable in the range 5-20 V [5, 28].

The first studies on the LM2941 voltage regulators were primarily focused on the enhanced-low-dose-rate-sensitivity (ELDRS) effects. In addition to the LM185 voltage regulator, the initial examinations were also performed on the LM2941J voltage regulator [28]. These devices were examined in the field of ^{60}Co γ-radiation for total ionising doses up to 500 Gy(SiO_2). Tests were implemented with three different dose rates, *i. e.* low dose rate (80 Gy/s) and high dose rate (138 cGy/s), both at room temperature, as well as an accelerated test with a medium dose rate (1 cGy/s) at an ambient temperature of 100 °C (elevated temperature irradiation) [28]. Relative variations of the output voltage were analysed for an input voltage of 6.9 V and for load currents from 60 mA up to 600 mA. Results presented in [28] indicated that the accelerated test was not a good predictor of failure at low dose rates for the LM2941J voltage regulator; the output voltage decreased by more than 2% following deposition of a total ionising dose of 200 Gy(SiO_2). In total, the output voltage decreased by 5% after deposition of a total dose of 500 Gy(SiO_2) for a load current of up to 300 mA [28].

The next study published on LM2941 voltage regulators was more extensive and was dedicated to the analysis of four different voltage regulators [29]. Voltage regulators from two different production lots were tested in a low dose rate γ-radiation field with a dose rate of 50 Gy/s and a total dose of up to 350 Gy(SiO_2) [29]. A part of the voltage regulators were irradiated unbiased, while the bias conditions for other group were $V_{in} = 6$ V, $I_{load} = 1$-10 mA. The results were mixed. Catastrophic failures of unbiased LM2941 voltage regulators were observed after the deposition of total doses of 190-240 Gy(SiO_2), when the output voltage fell to 0 V. On the other hand, researchers reported some degradation of the biased circuits; however, without their catastrophic failure [29]. Damage in the biased samples was two to three times less than that for the unbiased circuits [29].

In general, previous research has highlighted some weaknesses of the technological process implemented for the creation of LM2941 voltage regulators, especially for unbiased devices in the fields of low dose rate gamma radiation [28, 29]. On the other hand, the results were not so bad for biased LM2941 circuits in the high dose rate fields [28, 29]. Therefore, researchers continued with the analysis of the LM2941 voltage regulator and matched bipolar technological process. The next study was dedicated to the new version of the "ELDRS-free" LM2941W voltage regulator, recommended for space applications with an ultra-low dose rate environment and total doses of up to 1 kGy(SiO_2) [5]. These devices were made by the "National Semiconductor" facility in Greenock, United Kingdom, with the implementation of a new technological process [5]. The devices were again tested in a γ-radiation environment with low dose rate (100 Gy/s) and ultra-low dose rate (10 Gy/s) for doses up to 200 Gy(SiO_2) [5]. Also, a high dose rate experiment was performed with a dose rate of 180 cGy/s and total doses of up to 1 kGy(SiO_2) [5]. Voltage regulators were exposed to gamma radiation both in unbiased and biased conditions. Biased circuits were loaded with 5-50 mA, while the input voltage was 25 V [5].

In this case, the authors reported excellent characteristics of all the examined voltage regulators. The presented research was more thorough than the previous two had been and in this case, a wide range of parameters (output voltage, quiescent current, line regulation, dropout voltage, ripple rejection) was examined [5]. None of the specified parameters showed significant degradation, regardless of the LM2941W voltage regulator's operation in high dose rate or low dose rate fields or of the circuit's bias conditions [5].

Results presented by Kruckmeyer in [5] were quite different from the previous two studies [28, 29]; however, they justified the efforts that the authors of this paper have committed to the examination of the LM2940CT5 voltage regulator as a cheap replacement for specially designed radiation-hard components [10-12, 15]. Unfortunately, samples of LM2940CT5 voltage regulators from batches PM44AE and JM41AD were procured in 2004, before the implementation of the new technological process at the "National Semiconductor" wafer facilities. Therefore, they proved themselves as utterly radiation-sensitive components. There are many data in [5] that enable mutual comparison between the recorded characteristics of the LM2940CT5 integrated circuits and the LM2941W devices. In [5], there are data on the output voltage, dropout voltage and quiescent current, as there are in this manuscript and in previous papers [10-12, 15]; however, Kruckmeyer and associates did not collect data on quiescent current simultaneously from the loaded and unloaded voltage regulators. Therefore, it was not possible to perform a comparison with data on the serial pnp transistor's base current and forward emitter current gain, as may be seen in the presented research and in [10, 11, 15].

On the other hand, an examination of the older technological bipolar process, used for the manufacture of the LM2940CT5 voltage regulators, enabled better insight into the annealing mechanisms of the oxide trapped charge, as well as a more comprehensible understanding of the high load current influence on the recovery of irradiated low-dropout voltage regulators.

CONCLUSIONS

Examinations of the collector-emitter voltage of lateral serial pnp transistors in the voltage regulator LM2940CT5 provided plain data on the low radiation tolerance of this circuit, that was not explicitly presented during the examinations of dropout voltage with moderate load current. Higher and volatile serial transistor dropout voltage, and primarily decline of output voltage below the threshold of 4.9 V, regardless of the bias conditions, led to an unequivocal conclusion on the circuit's low radiation hardness. The main reasons for the decreased ability of the voltage regulator LM2940CT5 to keep a stable and satisfying output voltage were the loss of gain of the negative feedback reaction and, to a lesser extent, the decrease in the serial transistor's forward emitter current gain.

The magnitude of the load current had a significant influence on the radiation hardness of the voltage regulators LM2940CT5. Regardless of the greater degradation of the serial transistor's forward emitter current gain in the heavily loaded samples during the irradiation, total radiation hardness of voltage regulators LM2940CT5 operating with high load currents, slightly increased. The primary mechanism for improvement of the radiation hardness of the entire voltage regulator LM2940CT5 was the high-current-density flow through the serial transistor's emitter contact immediately above the isolation oxide. However, this oxide-trapped charge annealing reduced the beneficial influence of the oxide-trapped charge on the current gain of the power pnp transistors. But the high recombination of trapped charge with electrons from high-current-density flow in the proximity of the isolation oxide reduced the total concentration of the oxide-trapped charge and therefore caused the recovery of a number of small-signal npn transistors in the error amplifier circuit. The secondary mechanism for improvement of the voltage regulator's radiation hardness was passivation of negative interface traps in the base area of the lateral pnp transistor, owing to the high-density hole current in the base immediately below the isolation oxide. The passivation of the interface traps in the serial transistor's base area improved the radiation hardness of the serial transistor.

Consequently, the positive influence of the reduced concentration of oxide-trapped charge on the negative feedback reaction circuit, together with the positive influence of the reduced interface traps concentration in the lateral power transistor, exceeded the negative influence of annealed oxide-trapped charge on the serial pnp transistor's forward emitter current gain. The overall result of these effects was a slightly improved radiation tolerance of the voltage regulator LM2940CT5, but below the demands for proper operation of this circuit in a radiation environment.

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AUTHOR CONTRIBUTIONS

Theoretical analysis was carried out by V. Dj. Vukić and P. V. Osmokrović. Experiment was accomplished by V. Dj. Vukić. Both authors have analyzed and discussed the results. The manuscript was written and the figures were prepared by V. Dj. Vukić.

REFERENCES

[1] Adell, P. C., *et al*., Total Dose Effects in a Linear Voltage Regulator, *IEEE Transactions on Nuclear Science, 51* (2004), 6, pp. 3816-3821

[2] Pease, R. L., *et al*., Enhanced Low-Dose-Rate Sensitivity of a Low-Dropout Voltage Regulator, *IEEE Transactions on Nuclear Science, 45* (1998), 6, pp. 2571-2576

[3] Beaucour, J., *et al*., Total Dose Effects on Negative Voltage Regulator, *IEEE Transactions on Nuclear Science, 41* (1994), 6, pp. 2420-2426

[4] Ramachandran, V., *et al*., Modeling Total-Dose Effects for a Low-Dropout Voltage Regulator, *IEEE Transactions on Nuclear Science, 53* (2006), 6, pp. 3223-3231

[5] Kruckmeyer, K., *et al*., Low Dose Rate Test Results of National Semiconductor's ELDRS-Free Bipolar Low Dropout (LDO) Regulator, LM2941 at Dose Rates of 1 and 10 mrad(Si)/s, IEEE Radiation Effects Data Workshop, 2009, pp. 59-64

[6] Pease, R. L., Recent Advances in Understanding Total-Dose Effects in Bipolar Transistors, *IEEE Transactions on Nuclear Science, 56* (2009), 4, pp. 1894-1908

[7] Johnston, A., *et al*., Dose Rate Effects in Linear Bipolar Transistors, *IEEE Transactions on Nuclear Science, 58* (2011), 6, pp. 2816-2823

[8] Kelly, A. T., *et al*., Total Dose and Single Event Transients in Linear Voltage Regulators, *IEEE Transactions on Nuclear Science, 54* (2007), 4, pp. 1327-1334

[9] Chen, D., *et al*., Enhanced Low Dose Rate Sensitivity at Ultra-Low Dose Rates, *IEEE Transactions on Nuclear Science, 58* (2011), 6, pp. 2983-2990

[10] Vukić, V. Dj., Minimum Dropout Voltage of Serial pnp Transistor in Moderately Loaded Voltage Regulator in Gamma Radiation Field, *Nucl Technol Radiat, 27* (2012), 4, pp. 333-340

[11] Vukić, V., Osmokrović, P., Impact of Forward Emitter Current Gain and Geometry of pnp Power Transistors on Radiation Tolerance of Voltage Regulators, *Nucl Technol Radiat, 25* (2010), 3, pp. 179-185

[12] Vukić, V., Osmokrović, P., Total Ionizing Dose Degradation of Power Bipolar Integrated Circuit, *Journal of Optoelectronics and Advanced Materials, 10* (2008), 1, pp. 219-228

[13] Messenger, G. C., Ash, M. S., The Effects of Radiation on Electronic Systems, Van Nostrand Reinhold, New York, USA, 1992, pp. 332-340

[14] Gray, P., *et al*., Analysis and Design of Analog Integrated Circuits, J. Wiley & Sons, New York, USA, 2001, pp. 25-26, 88-89

[15] Vukić, V., Osmokrović, P., 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), 2, pp. 152-164

[16] Murkland, J. R., Congdon, J. S., Lateral pnp Power Transistor, United States Patent 4417265, November 22, 1983

[17] Khader, W. N., Wang, J. T., Hollins, B. E., Simplified BiFET Process, United States Patent 4512815, April 23, 1985

[18] Krishna, S., Ramde, A. R., Integrated Circuit Lateral Transistor Structure, United States Patent 4804634, February 14, 1989

[19] ***, LM2940 1A Low Dropout Voltage Regulator, National Semiconductor Corporation, Santa Clara, Cal., USA, 2003

[20] Holmes-Siedle, A., Adams, L., Handbook of Radiation Effects, Oxford University Press, New York, USA, 2004, pp. 211-213, 86-91, 478-479

[21] Pershenkov, V. S., *et al*., The Effect of Emitter Junction Bias on the Low Dose-Rate Radiation Response of Bipolar Devices, *IEEE Transactions on Nuclear Science, 44* (1997), 6, pp. 1840-1848

[22] Shaneyfelt, M. R., *et al*., Field Dependence of Interface-Trap Buildup in Polysilicon and Metal Gate MOS Devices, *IEEE Transactions on Nuclear Science, 37* (1990), 6, pp. 1632-1640

[23] Schmidt, D. M., *et al*., Modeling Ionizing Radiation Induced Gain Degradation of the Lateral PNP Bipolar Junction Transistor, *IEEE Transactions on Nuclear Science, 43* (1996), 6, pp. 3032-3039

[24] Djorić-Veljković, S. M., *et al*., Annealing of Radiation-Induced Defects in Burn-In Stressed Power VDMOSFETs, *Nucl Technol Radiat, 26* (2011), 1, pp. 18-24

[25] Oldham, T. R., McLean, F. B., Total Ionizing Dose Effects in MOS Oxides and Devices, *IEEE Transactions on Nuclear Science, 50* (2003), 3, pp. 483-499

[26] Baze, M. P., Plaag, R. E., Johnston, A. H., Dose Dependence of Interface Traps in Gate Oxides at High Levels of Total Dose, *IEEE Transactions on Nuclear Science, 36* (1989), 6, pp. 1858-1864

[27] Vukić, V., Osmokrović, P., Total Ionizing Dose Response of Commercial Process for Synthesis of Linear Bipolar Integrated Circuits, *Journal of Optoelectronics and Advanced Materials, 8* (2006), 4, pp. 1538-1544

[28] Abare, W., *et al*., Comparative Analysis of Low Dose-Rate, Accelerated, and Standard Cobalt-60 Radiation Response Data for a Low-Dropout Voltage Regulator and a Voltage Reference, IEEE Radiation Effects Data Workshop, 2002, pp. 177-180

[29] Chavez, R. M., *et al*., Total Ionizing Dose Effects in Bipolar and BiCMOS Devices, IEEE Radiation Effects Data Workshop, 2005, pp. 144-148

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ЛАТЕРАЛНИ ПНП ТРАНЗИСТОР СНАГЕ У РАДУ СА ВЕЛИКОМ ГУСТИНОМ СТРУЈЕ У СТАБИЛИЗАТОРУ НАПОНА ИЗЛОЖЕНОМ ЗРАЧЕЊУ

Рад латералних пнп транзистора снаге у пољу гама зрачења испитиван је одређивањем минималног пада напона на веома оптерећеним стабилизаторима са малим губицима LM2940CT5. Демонстрирана је мала радијациона отпорност стабилизатора напона, са неприхватљиво ниским вредностима излазног напона и непостојаним напоном колектор–емитор на редном транзистору. Заједно са претходним резултатима о струји базе и коефицијенту струјног појачања редних транзистора, било је могуће одредити позитиван утицај велике струје потрошача на извесно повећање радијационе отпорности стабилизатора напона LM2940CT5. Протицање струје велике јачине кроз широки алуминијумски контакт емитора редног транзистора изнад изолационог оксида довело је до интензивне рекомбинације позитивног наелектрисања захваћеног у оксиду, изазивајући смањење струјног појачања латералног пнп транзистора, али и интензиван опоравак нпн транзистора за мале сигнале у регулационом колу. Велика густина струје у области базе латералног пнп транзистора непосредно испод изолационог оксида смањила је концентрацију негативних спојних захвата наелектрисања. Тако је позитиван утицај велике струје потрошача на коло негативне повратне спреге, заједно са повољним ефектом смањења концентрације спојних захвата, био већи од негативног утицаја смањења концентрације наелектрисања у оксиду на коефицијент струјног појачања редног латералног пнп транзистора.

Кључне речи: коефицијенш сшрујноī йојачања, лашерални йнй шранзисшор, сшабилизашор найона, īусшина сшрује, захваћено наелекшрисање у оксиду, сйојни захваш наелекшрисања, īама зрачење, каракшерисшика найонске реīулације