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ON-LINE MONITORING OF BASE CURRENT AND FORWARD EMITTER CURRENT GAIN OF THE VOLTAGE REGULATOR'S SERIAL PNP TRANSISTOR IN A RADIATION ENVIRONMENT

by

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A method of on-line monitoring of the low-dropout voltage regulator's operation in a radiation environment is developed in this paper. The method had to enable detection of the circuit's degradation during exploitation, without terminating its operation in an ionizing radiation field. Moreover, it had to enable automatic measurement and data collection, as well as the detection of any considerable degradation, well before the monitored voltage regulator's malfunction. The principal parameters of the voltage regulator's operation that were monitored were the serial pnp transistor's base current and the forward emitter current gain. These parameters were procured indirectly, from the data on the voltage regulator's load and quiescent currents. Since the internal consumption current in moderately and heavily loaded devices was used, the quiescent current of a negligibly loaded voltage regulator of the same type served as a reference. Results acquired by on-line monitoring demonstrated marked agreement with the results acquired from examinations of the voltage regulator's maximum output current and minimum dropout voltage in a radiation environment. The results were particularly consistent in tests with heavily loaded devices. Results obtained for moderately loaded voltage regulators and the risks accompanying the application of the presented method, were also analyzed.

Key words: forward emitter current gain, base current, pnp transistor, on-line monitoring, voltage regulator, quiescent current, gamma radiation

INTRODUCTION

A recently presented method of examining the characteristic of a voltage regulator in a radiation field has presented us with the possibility of tracing the changes in a serial pnp transistor's forward emitter current gain without performing direct measurements on the chip [1]. For the forward emitter current gain to be calculated, it was necessary to procure data on the serial transistor's base current (I_B), as well as on its collector current (I_C). Measurements of the quiescent current for an unloaded voltage regulator (I_{Q0}) provided the value of the integrated circuit's internal consumption. The subtraction of the unloaded circuit's quiescent current from the quiescent current of the device loaded to the maximum (I_Q), for same input voltages, gave a value of the serial transistor's base current [1]. Once the load current of the voltage regulator, *i. e.* the serial transistor's collector current is known, the serial transistor's forward emitter current gain can be calcu-

lated [1]. The serial transistor's current gain is found as the ratio of its collector current to its base current.

However, this method cannot be applied if the examined device requires an uninterrupted operation in a radiation environment. Moreover, even when it is possible to terminate the irradiation, measurements at specified points require significant time and labor. The need for the acceleration or automation of the experiment put aside, the necessity for constantly monitoring operating voltage regulators in a radiation environment is reason enough for considering a novel method of determining the serial transistor's parameters in a low-dropout voltage regulator.

THEORY

Voltage regulators are widely used as components that receive fluctuating dc input voltage and turn it into a constant, well specified output voltage, with variations in the supply voltage essentially eliminated [2]. A common type of a voltage regulator is the series

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regulator, which has the output voltage controlled by a power transistor connected in series with the output. The power transistor is the last stage of a high-gain voltage amplifier and may be of the npn, super-β, Darlington, or pnp type. If a low-dropout voltage is required on the serial transistor, a pnp power transistor is usually used.

An important characteristic of low-dropout voltage regulators with a serial pnp power transistor is the relatively high quiescent current. This current is comprised of the serial transistor's base current and the control circuit's internal consumption current. The serial transistor's base current is calculated by subtracting an unloaded device's quiescent current from the quiescent current of an operating device. Another important fact is that the values of quiescent currents in low-dropout voltage regulators are relatively high (usually from 5 mA up to 50 mA). This characteristic enables direct measurement of the voltage regulator's quiescent current with ordinary laboratory equipment. Since serial pnp power transistors are usually assembled of many elementary pnp transistors connected in parallel, it is easy to calculate the values of base currents even for elementary transistors by dividing the calculated serial transistor's base current with the number of elementary pnp transistors.

The aforementioned characteristics of the quiescent current in low-dropout voltage regulators are important for establishing a method of on-line monitoring of the serial pnp transistor's operational status. Some authors have concluded that the main reason for the radiation-induced degradation of low-dropout voltage regulators was the collapse of the forward emitter current gain in lateral serial pnp power transistors [3, 4]. Others identified the decrease of the current gain of multicollector pnp transistors with lateral emitters in the start-up circuit as the weak point in irradiated voltage regulators [5, 6]. These results suggest that if the most sensitive elements in voltage regulators are monitored, the detection of considerable degradation may be possible, well before these devices fail in a radiation environment.

EXPERIMENT

Materials and methods

Integrated 5-volt positive commercial-off-the-shelf voltage regulators LM2940CT5 and L4940V5 were tested at the Vinča Institute of Nuclear Sciences, Belgrade, Serbia.

LM2940CT5 circuits were from the PM44AE batch made by the "National Semiconductor's" subcontractor in China. The circuits were packaged in Malacca, Malaysia. The L4940V5 devices were from the WKOOGO 408 batch made by "STMicroelectronics" in China [1].

^{60}Co was used as a γ-ray source, positioned within the IRPIK-B device for gamma field realization. The adopted mean energy of γ photons was $E_\gamma =$ = 1.25 MeV. The samples were irradiated at the mouth of the collimator.

Measurements of the exposure were performed with a "Dosimentor" PTW M23361 ionization chamber with a volume of $3 \cdot 10^{-5}$ m^3 and a DI4 reader attached to it [7].

The devices were irradiated up to a total dose of 500 Gy, at a dose rate of 4 cGy/s. The reader showed values of exposure in units of roentgen (R) which were then converted to the absorbed dose in silicon dioxide (SiO$_2$) by using the mass, energy-absorption coefficients for silicon dioxide and air [8]. The practice of converting all dose values to Gy(SiO$_2$) enables a direct comparison of gamma and X-ray data. The main argument for this approach is that radiation-induced damage in the oxide is the primary cause of degradation in an integrated circuit. Exposure to ionizing radiation leads to the creation of oxide trapped charge and interface traps which have a dominant influence on irradiated electronic components. However, since all of the presented results were obtained in a gamma radiation field, there is practically no difference between the doses absorbed in silicon and silicon dioxide (Gy(Si) and Gy(SiO$_2$), respectively). The reason is that mass energy-absorption coefficients for silicon and silicon dioxide have approximately the same values at the photon energy of 1.25 MeV [9].

Samples of LM2940CT5 and L4940V5 voltage regulators were irradiated in groups of four. Cables ten meter long powered the devices. Beside the power supply cables, sense cables of the same length were laid. To suppress the negative influence of long supply cables, 33 μF electrolytic capacitors were mounted at the input contacts of the integrated circuits. According to the manufacturer's recommendation, capacitors of the same kind were mounted on the integrated circuit output contacts as well, in order to maintain operation stability of the low-dropout voltage regulators. None of the previous experiments showed any malfunctioning of the mounted electrolytic capacitors [7]. Moreover, data specified in literature suggest that the total dose effects in electrolytic capacitors are negligible below an absorbed dose of about 100 kGy [9, 10]. There were, therefore, no attempts to use other kinds of capacitors with more radiation tolerant dielectric materials.

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

The principal quantities used for detecting the degradation of the voltage regulator due to exposure to ionizing radiation were the forward emitter current gain and the base current of the serial transistor. Elec-

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trical quantities measured in these experiments were the voltage regulator's output voltage 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 [1]

$$I_B = I_Q\big|_{(I_C = I_{load})} - I_{Q_0}\big|_{(I_C = 0)} \qquad (1)$$

In low-dropout voltage regulators that operate with a load current of 1 mA, the serial transistor's base current is negligible. It was, therefore, assumed that the entire quiescent current of the low-current device is approximately equal to the quiescent current of the unloaded voltage regulator. In other words, a quiescent current of negligibly loaded devices was assumed to be equal to the internal control circuit's consumption current in voltage regulators with load currents equal to 100 mA and 500 mA. This approximation was based on the fact that load currents of virtually unloaded devices differ by two orders of magnitude from those of moderately and heavily loaded devices.

Irradiation tests were performed on devices with the same input voltage of 8 V and three different values of load currents: 1 mA, 100 mA, and 500 mA. The method established for on-line detection of the serial pnp transistor's base current was the subtraction of the quiescent current of circuits loaded with 1 mA from the quiescent current of devices with load currents equal to 100 mA and 500 mA. In that way, it was possible to calculate the serial transistor's base current for samples loaded with 100 mA and 500 mA. Measurements of output voltages and quiescent currents were performed once the predetermined gamma radiation total doses of 10 Gy were reached, *i. e.* every 250 seconds, at the dose rate of 4 cGy/s. The serial transistor's forward emitter current gain (β) was determined as the ratio between the output current of the voltage regulator and the calculated value of the base current [1]

$$\beta = \frac{\partial I_C}{\partial I_B} \approx \frac{I_C}{I_B} \qquad (2)$$

The output current of the low-dropout voltage regulator is, actually, its serial transistor's collector current. All of the previously stated facts have provided us with the possibility of performing simple measurements on irradiated devices and calculating the forward emitter current gain of the serial transistor without a need to interrupt the irradiation.

Voltage regulators were loaded with variable resistors with a total resistance of 50 Ω. Constant output current was maintained by changing the potentiometer's resistance, according to the variations of the output voltage. In the experimental setup, instead of an ordinary variable resistor, a programmable load may also be used. Since the manufacturer requires the use

of minimum output electrolytic capacitors of 22 μF [11, 12], both in the case of LM2940CT5 and L4940V5 circuits, voltage regulators always operate with a combined, resistive – capacitive (RC) load. However, the output parameters of a low-dropout voltage regulator are of a direct voltage and current, with a very small ripple. Therefore, since the output value is not an alternate current, the load type is not significant as far as static characteristics are concerned. Only if the transient responses of the low-dropout voltage regulators were to be analyzed, connected passive elements, as well as the stray capacitances and inductances, would be of consequence. Yet, since the topic of this paper is on-line monitoring of a serial power transistor's static characteristics, the analysis of various load types, such as LC or RLC, are not of primary interest. Consequently, the experimental setup represents a faithful simulation of real electronic devices, such as microcontrollers with additional integrated circuits and their passive components.

In our research, the operation of voltage regulators LM2940CT5 and L4940V5 was also analyzed with different dose rates, as well as with various sources of radiation [7, 13, 14]. Low-dropout voltage regulators were examined with a dose rate of 5.5 cGy/s, in a ^{60}Co field. Moreover, the X-radiation source of the mean photon energy of 150 keV was used, with the dose rate of 11.6 cGy/s [14]. In above cited experiments, samples of voltage regulator LM2940CT5 were irradiated up to the total ionizing dose of 3 kGy [7], while some samples of integrated circuits L4940V5 were even exposed to a dose of 11 kGy [14]. Therefore, an extremely wide range of tests were carried out, with various types of radiation, total ionizing doses and dose rates. The irradiation of the tested voltage regulators LM2940CT5 and L4940V5 with higher dose rates did not lead to significantly different responses. This is particularly true of voltage regulators of the L4940V5 type which demonstrated high radiation hardness in relation to various types of radiation environment and different dose rates. Yet, examinations of specified integrated circuits with lower dose rates was of less interest, especially in cases of very low dose rates. The reason was the detailed analysis of the low-dose-rate data published in literature. This was particularly true of low-dropout voltage regulators ("National Semiconductor", LM2941) [15, 16], variable voltage regulators created in the same technological process as the five-volt LM2940CT5 regulators. As in the case of research on low-dropout voltage regulators of the LM2940CT5 type with medium-dose-rates, tests of LM2941 devices with low-dose-rates exhibited high radiation sensitivity typical of this family of voltage regulators. Likewise, the implemented "National Semiconductor" process for the creation of monolithic bipolar integrated circuits proved to be radiation sensitive.

A low-dropout voltage regulator, "STMicroelectronics" L4913 [17], was also examined in the
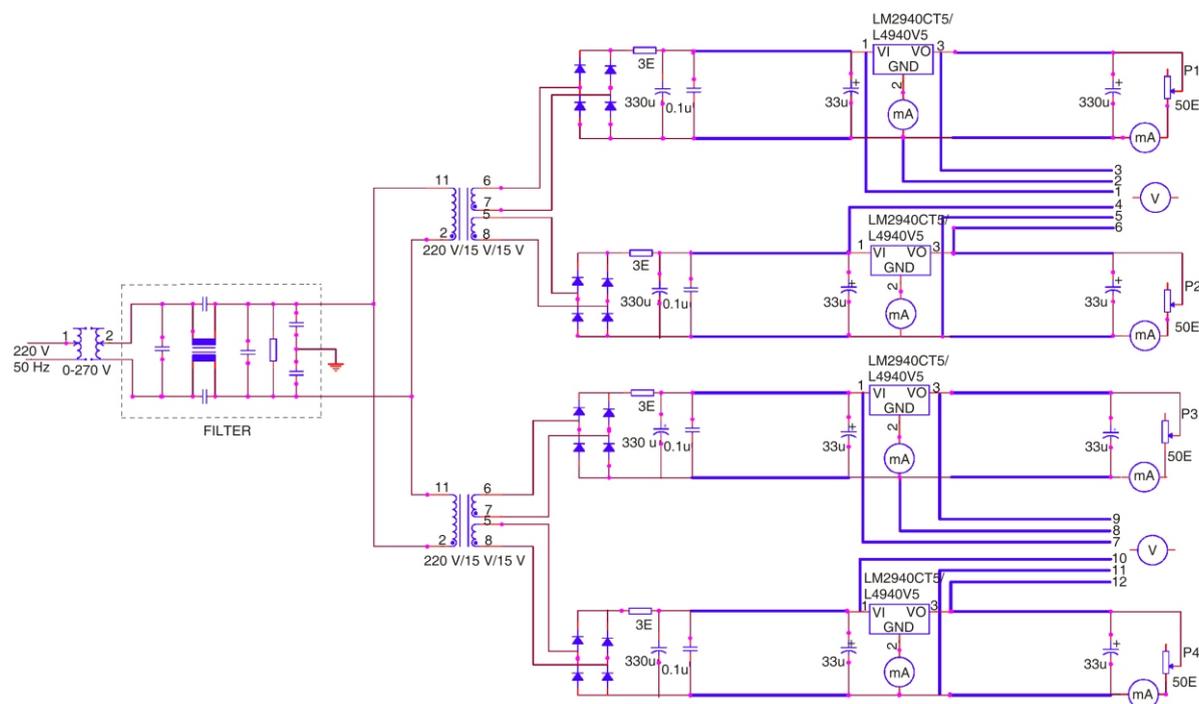
Figure 1. Schematic circuit diagram of the experimental set-up used for the examination of voltage regulators LM2940CT5 and L4940V5

low-dose-rate field of ^{60}Co. This voltage regulator demonstrated very high radiation hardness [17], as did the circuit of the same manufacturer, L4940V5, in ^{60}Co and X-radiation fields [13, 14]. In general, it was accepted that the operation of bipolar integrated circuits in a low-dose-rate γ-radiation environment significantly reduces radiation tolerance of the irradiated devices [9].

In fig. 1, a schematic diagram of the experimental setup used for examining voltage regulators LM2940CT5 and L4940V5 in the γ radiation field is presented.

Characteristics of examined integrated circuits

LM2940CT5 and L4940V5 are three-terminal low-dropout voltage regulators, packaged in standard TO-220 cases. During irradiation and tests, all voltage regulators were operated with heatsinks whose thermal resistance was 14 K/W. The main electrical and thermal characteristics of these linear bipolar integrated circuits are presented in tab. 1.

Voltage regulator "National Semiconductor" LM2940CT5 is an analog integrated circuit created in a conventional process of manufacturing monolithic-silicon junction-isolated integrated circuits [18]. The main area of the chip is occupied by a pnp pass

Table 1. Characteristics of voltage regulators LM2940CT5 and L4940V5 [11, 12]

Parameter	Unit	Conditions	LM2940CT5	L4940V5
Output voltage (V_{out})	V	V_{in} = 10 V, I 1A	4.85-5.15	4.9-5.1
Maximum input voltage	V		26	17
Line regulation	mV	I_{out} = 5mA	20	4
Load regulation	mV	50 mA I_{out} 1 A	35	8
Dropout voltage	V	I_{out} = 1 A	0.5	0.5
Quiescent current (I_q)	mA		10	5
Short circuit current	A		1.6	1.5
Ripple rejection	dB	f_{out} = 120 Hz, I_{out} = 100 mA, V_{in} = 1 V	72	68
Minimum output capacitor	F		22	22
Minimum input capacitor	F		0.47	0.1
Thermal resistance junction-to--ambient (case TO-220)	°C/W		53	50
Temperature range	°C		0 : 125	–40 : 150

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transistor and its driver transistor. The serial pnp transistor consists of 350 parallelly connected pnp transistors and provides a maximum output current of about 1050 mA for β = 15-20, with a quiescent current of 50-60 mA [11, 19]. Each transistor can provide a current of 3 mA, while greater current capacity is achieved by their parallel connection in structures with ballasting resistors. For the applied bipolar process, the values of a single pnp transistor are: β = 24 (for I = 1 mA), BV_{CB0} = 94 V (collector-emitter breakdown voltage with the base open), f_T = 2.5 MHz (cut-off frequency) [18].

The pass pnp transistor consists of smaller groups, comprised of 18 and 24 basic pnp transistors, where the major group counting 24 transistors is closer to the input base terminal, while the minor group is situated between the collector and emitter pads. The area of a pnp power transistor is about 2.4 mm^2, while the area of a pnp driver transistor, assembled from 70 basic pnp transistors, is about 0.5 mm^2. Altogether, these power transistors occupy about two thirds of the chip area [19].

The layout of a pnp power transistor is shown in fig. 2, the cross-sections (area no. 5 in fig. 2) in fig. 3 [19]. In fig. 2, transistors are grouped in sections of six and nine elements, divided by ballast resistors. Emitters are round, approximately 13 μm in diameter. Between the emitters and the collector diffusion region are the base rings, which belong to the n-type epitaxial layer [19].

Schematic circuit diagram of the voltage regulator LM2940CT5 is presented in fig. 4. More details on the implemented technological process, the construction of the lateral pnp transistor, and on voltage regulator LM2940CT5 are to be found in [7, 8, 11, 18, 19].

The "STMicroelectronics" L4940V5 voltage regulator was commercially made in a 20 V
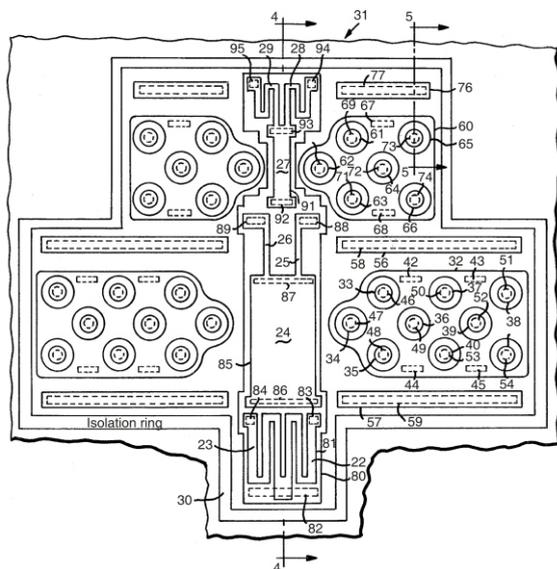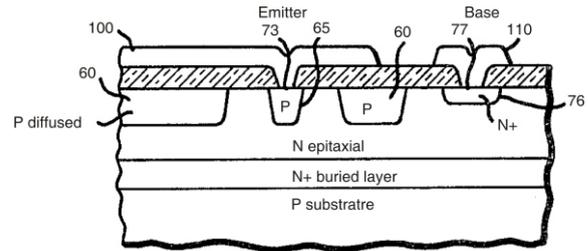

Figure 3. Cross-section (area no. 5) of a single pnp transistor from fig. 2 [19]

"Multipower" HDS^2/P^2 process ("High Density Super Signal / Power Process") [20]. This process provides the possibility of creating both MOS and bipolar components on the same wafer. It also enables the synthesis of an isolated collector vertical pnp transistor (ICV PNP), vertical npn transistor (V NPN) and low-leakage diode (LLD) [20], as can be seen in fig. 5. The procedure for isolating the pnp transistor's collector was realized by junction isolation, including additional lateral isolation of the base and collector by a local oxide. The said procedure, when utilized in transistor edge regions, should have significantly reduced the integrated circuit's radiation hardness, if the synthesis of a "nested" emitter had not been performed. The "nested" emitter completely surrounds the emitter area by a highly doped n-type base region [20]. The implementation of the "Multipower" HDS^2/P^2 process resulted in high current densities in transistors: J = 6 A/mm^2 (npn transistor) and J = 2 A/mm^2 (pnp transistor, for V_{sat} = 1 V and h_{FE} = 10). The cut-off frequency, f_T, for small signal transistors in the integrated circuit, was in the range of 0.5-1.5 GHz [13, 21].

A double layer polycrystalline silicon was the basic semiconductor material used for the synthesis of the integrated circuit. At the beginning of the treatment, a p-silicon crystal was used, with a <100> Miller index orientation and a specific electrical resistance of ρ = 1-5 cm [13, 20]. A 500 nm thick insulator layer of SiO$_2$ was deposited over the entire surface of the silicon wafer. On top of the first SiO$_2$ layer, another oxide layer of the same thickness was deposited, with implanted phosphorus and boron ions (PBSG – phosphorus boron silicon glass). An alloy, comprised of 99% aluminium and 1% silicon, was deposited above the PBSG layer [13, 20].

Block-diagram of the voltage regulator LM2940CT5 is presented in fig. 6. Further details on the implemented technological process, construction of the isolated collector vertical pnp transistor and the L4940V5 voltage regulator are presented in [8, 12, 13, 20, 21].

Figure 2. Topology of a lateral pnp power transistor [19]

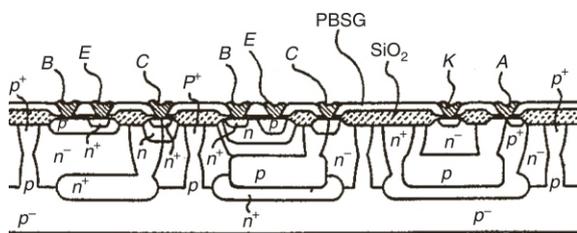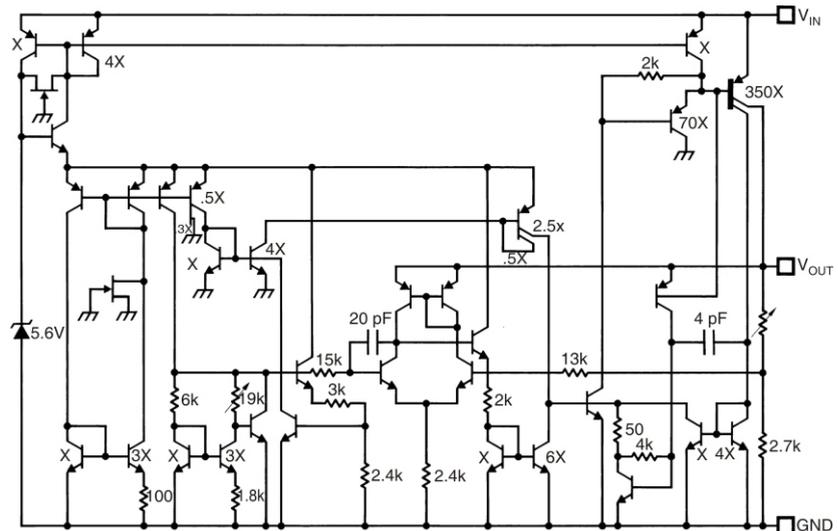**Figure 4. Circuit diagram of the voltage regulator LM2940CT5**

Figure 5. Realization of NPN and ICV PNP transistors and low-leakage diode in the "Multipower" HDS^2/P^2 process [13, 20]
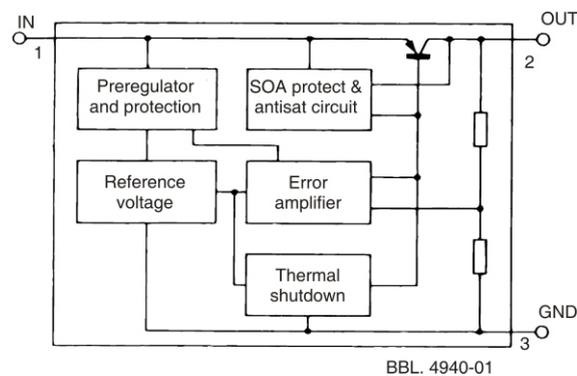

Figure 6. Block-diagram of the voltage regulator "STMicroelectronics" L4940V5 [12]

RESULTS AND DISCUSSION

Data presented in figs. 7-12 were obtained from tests with LM2940CT5 circuits. Figures 7 and 8 show complete data provided by on-line monitoring of the output voltage and the quiescent current of LM2940CT5 voltage regulators. The output voltage was most stable for samples with a negligible load cur-

rent and slightly less stable in devices loaded with 100 mA. Even at the outset of irradiation, voltage regulators with a load current of 500 mA couldn't reach
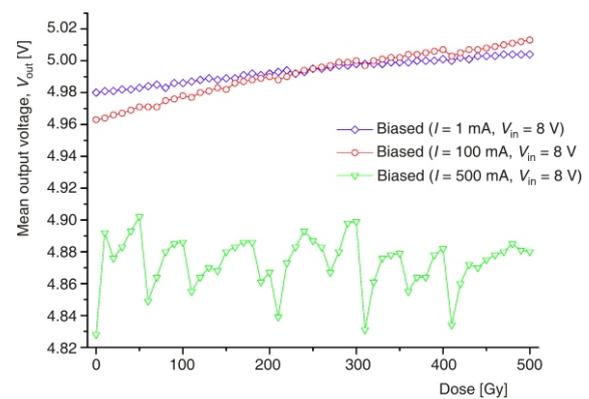

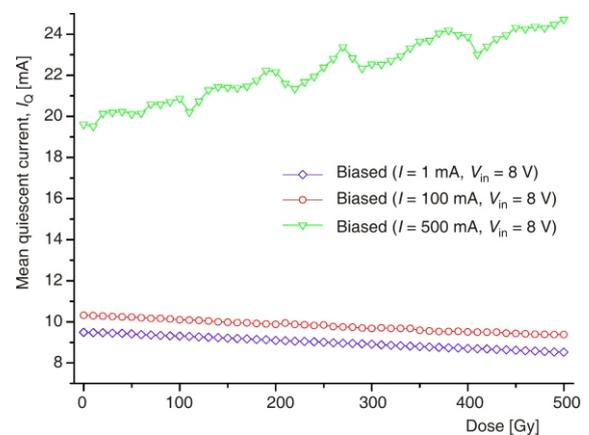**Figure 7. Change of the mean output voltage in voltage regulator LM2940CT5 under the influence of γ-radiation**

Figure 8. Change of the mean quiescent current in voltage regulator LM2940CT5 under the influence of γ-radiation

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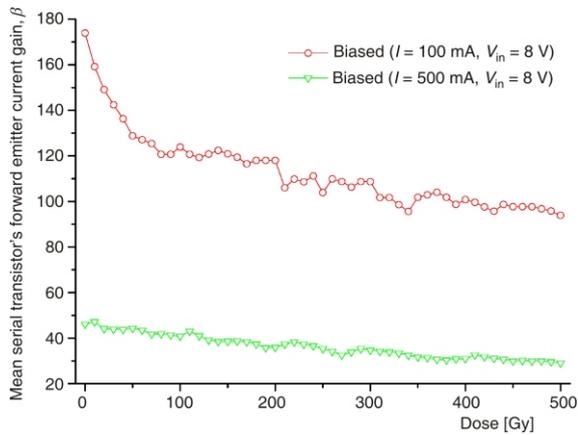

Figure 9. Change of mean serial transistor's forward emitter current gain in voltage regulator LM2940CT5 under the influence of γ-radiation

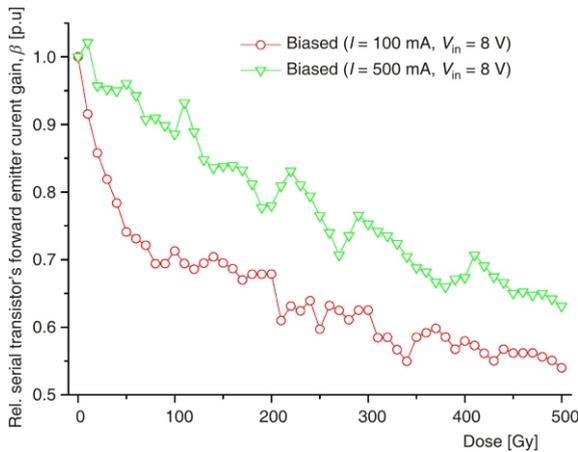**Figure 10. Change of relative serial transistor's forward emitter current gain in voltage regulator LM2940CT5 under the influence of γ-radiation**
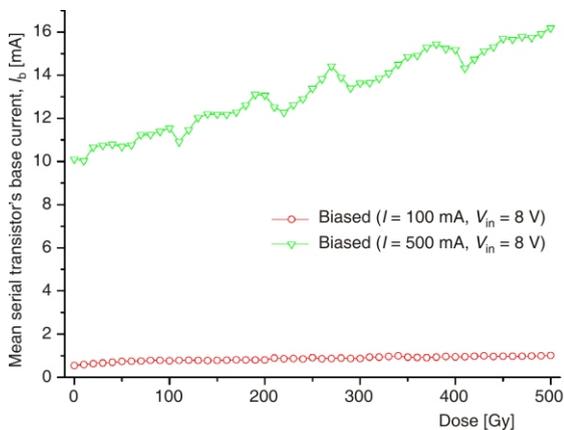

Figure 11. Change of mean serial transistor's base current in voltage regulator LM2940CT5 under the influence of -radiation
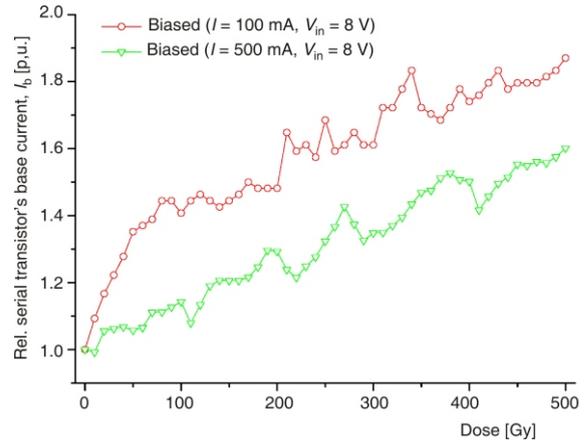

Figure 12. Change of the relative serial transistor's base current in voltage regulator LM2940CT5 under the influence of γ-radiation

the 4.9 V value of output voltage, remaining in an unacceptable range of 4.83-4.90 V throughout the entire process of irradiation. These results correspond well with previously observed drawbacks of LM2940CT5 voltage regulators, this having to do with the failure of the error amplifier circuit and a sharp decline of emitter injection efficiency immediately upon the start of irradiation, a cause of the abrupt decrease in the maximum output current [1, 7].

While in fig. 8 there are marked differences between quiescent currents of the devices loaded with 1mA and 500 mA, it is surprising how small these differences are between moderately and negligibly loaded devices. The minor difference between the latter pair of quiescent currents is due to the very small serial transistor's base current in voltage regulators with bias and load parameters of 8 V and 100 mA. In other words, the irradiated devices with the stated parameters operated with a large serial pnp transistor's forward emitter current gain. This is most evident in fig. 9, with an initial value of the forward emitter current gain of nearly 170, while the initial current gain of the heavily loaded devices was less than 50. As previously seen, this is a consequence of the fact that power serial pnp transistors operated at a high level of carrier injection into the emitter, in the far right area of the characteristic $\beta = f(V_{BE})$, *i. e.* $\beta = f(I_E)$. The heavily loaded samples worked at a much lower current gain than the lightly loaded ones, operating in the area of the serial pnp transistor's maximum current gain.

In calculating the serial transistor's forward emitter current gain for devices loaded with currents of 100 mA and 500 mA, the quiescent current of the nearly unloaded biased device ($V_{in} = 8$ V, $I = 1$ mA) was assumed to be approximately equal to the internal consumption current of the loaded devices, *i. e.* the assumed unloaded voltage regulator's quiescent current.

Due to the considerable difference between the quiescent currents of devices loaded with 500 mA and 1 mA, this approximation has a minor influence on the calculated values of base currents and forward emitter current gains. However, due to the small differences between moderately loaded and nearly unloaded devices, the assumption of the quiescent current of an unloaded device being equal to the moderately loaded circuit's internal consumption current had to be scrutinized.

Table 2 presents the measured values of the serial transistor's forward emitter current gains. Data were acquired by on-line monitoring, as well as by examinations of the maximum output current [1]. It is obvious that there are small discrepancies between the values of current gains, since the operating conditions are similar for voltage regulators irradiated with bias and load conditions of 8 V and 500 mA, on one side, and devices used for the determination of the maximum output current, on the other. As expected, forward emitter current gains of the circuits with a maximum load are lower than the values of their counterparts operating with the load current of 500 mA in a radiation environment. This is due to high carrier injection into the emitter and the negative feedback reaction [1].

Data in tab. 2 serve to justify the validity of adopting the unloaded voltage regulator's quiescent current as the heavily loaded circuit's internal consumption current. This assumption enabled us to adopt a suitable method for on-line monitoring of the serial transistor's forward emitter current gain and base current yet to be established. During the examination of the maximum output current, the tested devices operated with a load current between 400 mA and 600 mA, approximate values for the heavily loaded samples in a γ-radiation environment. However, heavily loaded voltage regulators LM2940CT5 demonstrated unacceptable values of the output voltage (lower than 4.9 V), even before the irradiation. Therefore, even this data disqualified voltage regulators LM2940CT5 for their implementation in a radiation environment. The underlying reason was not a slight variation of the output voltage, but the examined device's continuous operation with an unacceptably low output voltage.

In the case of the irradiated samples loaded with 100 mA, it was not easy to evaluate the novel method, since there were no similar operating conditions to be found in previously published papers. Moreover, in the group of four samples examined at 8 V and 100 mA, there were significant differences between the measured quiescent currents. The four values of the unloaded samples' quiescent currents measured before irradiation ranged between 9.49 mA and 9.88 mA, with the mean value of 9.76 mA. This mean value was close to the assumed unloaded circuit's quiescent current of 9.78 mA which is the mean value for samples biased with 8 V and loaded with 1 mA.

The mentioned differences between the quiescent currents become even more obvious when compared to the calculated serial transistor's base currents. These currents are in the range of 0.54 mA-1 mA, in case of operation with the input voltage of 8 V and output current of 100 mA. On the other hand, for the heavily loaded devices (V_{in} = 8V, I_{out} = 500 mA), the values of the calculated serial transistor's base currents were between 10.1 mA and 16.2 mA (fig. 11). The relative increase of the heavily loaded circuit's base current is smaller than the equivalent value in a moderately loaded device (fig. 12). Accordingly, degradation of the forward emitter current gain is also less expressed in the heavily loaded voltage regulators (fig. 10). Yet, very small absolute values of the base current, in comparison with the values of the entire quiescent current, may give rise to a large measurement uncertainty if the assumed values are used instead of the real ones. However, the exact values of the base currents are impossible to detect using the on-line monitoring method, if this is to be done without interrupting the irradiation process.

This example makes it clear that the selection of samples to be examined can have a crucial influence on the calculated base current and forward emitter current gain. The selection of the tested devices was of particular importance when the proposed on-line monitoring method was used on moderately loaded voltage regulators. On the other hand, in cases of heavily loaded voltage regulators, the values of the serial transistors' base currents were too large to be affected by the minor differences between the quiescent currents of the chosen samples.

There is another significant comment to be made regarding LM2940CT5 voltage regulators with a lateral pnp power transistor. Ramachandran and coworkers identified the Brokaw band-gap reference as one of the main causes for the observed degradation of the low-dropout voltage regulator "Micrel" 29372 [6]. The output voltage of the 29372 regulator increased slightly during the operation. As seen from fig. 7, the output voltage of both negligibly and moderately loaded devices increased slightly. Moreover, the rise

Table 2. Change of the serial transistor's forward emitter current gain in voltage regulator LM2940CT5 as a function of the total ionizing dose. The current gain was determined during the examination of the maximum output current [1] and the on-line monitoring of the irradiated devices' output and quiescent currents

Total dose, D [Gy]	β (I_{outmax}) [1]	β (on-line)
0	42.3	46.1
50	38	44.3
100	35.1	40.8
200	32.2	35.9
300	31.2	34.7
400	26.2	31
500	25.9	29.1

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of the output voltage in moderately loaded devices was more prominent than in the negligibly loaded ones. These characteristics point to a degradation mechanism similar to that of the voltage regulator 29372. The source of the referent voltage in LM2940CT5 devices ceased to operate, invariably. However, the degradation of LM2940CT5 voltage regulator's band-gap reference was much less expressed than the loss of the serial transistor's current gain.

Figures 13-18 present the experimental results obtained for L4940V5 voltage regulators. As in the case of the heavily loaded LM2940CT5 voltage regulators, during the experiment, there were some variations of the output voltage. However, contrary to LM2940CT5 circuits, the output voltage never fell below the threshold voltage of 4.9 V, as can be seen in fig. 13. However, as in the case of the LM2940CT5 voltage regulator, the input voltage during irradiation was not stabilized but, rather, transformed and rectified the power line voltage of 220 V and 50 Hz. As the varia-
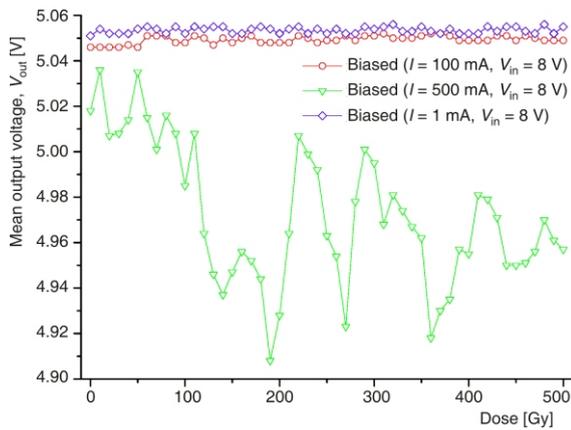

Figure 15. Change of the mean serial transistor's forward emitter current gain in voltage regulator L4940V5 under the influence of γ-radiation

Figure 16. Change of the relative serial transistor's forward emitter current gain in voltage regulator L4940V5 under the influence of γ-radiation

Figure 13. Change of mean output voltage in voltage regulator L4940V5 under the fluence of γ-radiation
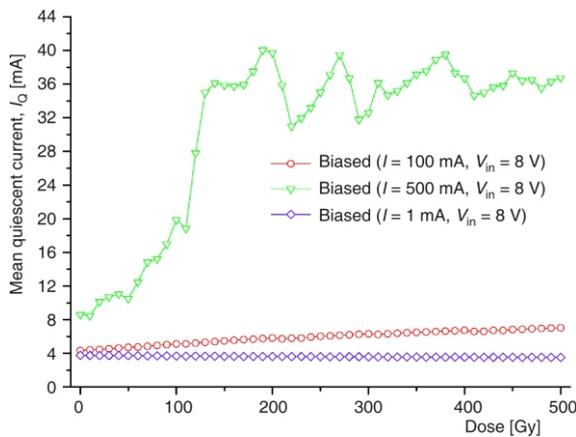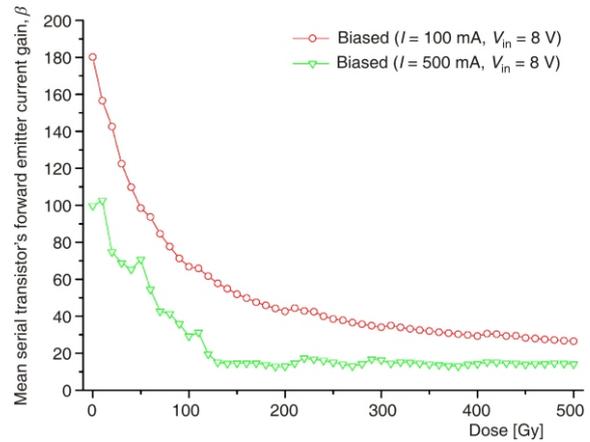

Figure 14. Change of mean quiescent current in voltage regulator L4940V5 under the influence of γ-radiation

Figure 17. Change of mean serial transistor's base current in voltage regulator L4940V5 under the influence of γ-radiation

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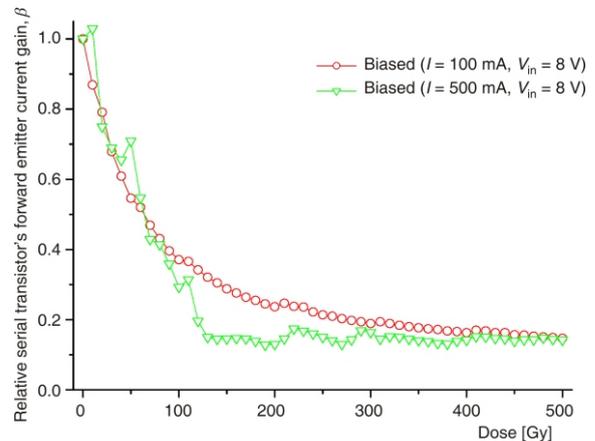**Figure 18. Change of relative serial transistor's base current in voltage regulator L4940V5 under the influence of γ-radiation**

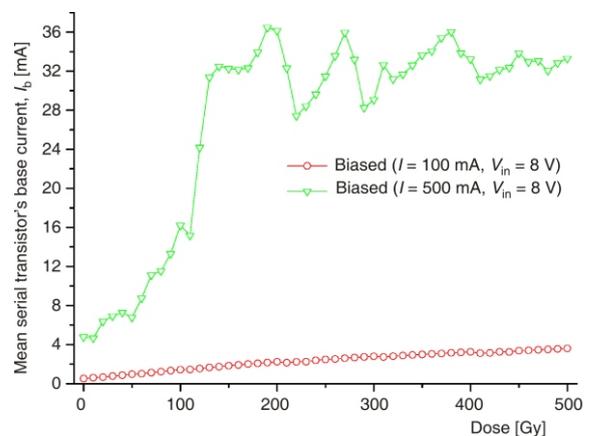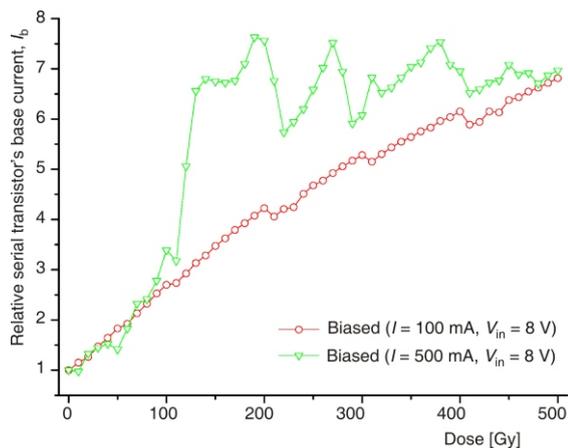tions appeared in the power line voltage, the input voltage also had some fluctuations that the voltage regulator corrected, while keeping the output voltage near the reference of 5 V. Line regulation characteristics of the heavily loaded irradiated circuit, along with the output voltage variations of nearly 100 mV, were above the values specified by the manufacturer (which don't pertain to the operation in a radiation environment). However, it did not affect the proper operation of the circuit.

Figure 14 demonstrates a clear trend of quiescent current increase in an ionizing radiation field. Moreover, the quick saturation of the heavily loaded samples' quiescent current is observed, as well. The trend was much more favorable for devices with a 100 mA load current than with the LM2940CT5 voltage regulators. The reason for this was a larger difference between the quiescent currents of the nearly unloaded ($I = 1$ mA) and moderately loaded ($I = 100$ mA) devices. The increasing difference between the serial transistors' base currents should enable an accurate estimation of their forward emitter current gains during the on-line monitoring of the irradiated devices.

The characteristics of the forward emitter current gain for devices with load currents of 100 mA and 500 mA are presented in figs. 15 and 16. They bear resemblance to previous results obtained through the examination of the maximum output current [1] and, even more so, the results of the change in the serial transistor's dropout voltage [8]. The sharp fall in the forward emitter current gain was, as previously reported, a consequence of increased recombination in the base area affected by the large serial transistor's perimeter-to-area ratio. An additional cause is the reaction of the negative feedback loop [1].

The increase in the base current in moderately and heavily loaded devices differs, as can be seen in figs. 17

and 18. For devices loaded with 500 mA, the base current quickly enters the saturation region (after the absorption of a total dose of approximately 120-130 Gy). The limitation of the base current was followed by operation with a nearly constant serial transistor's forward emitter current gain. On the other hand, in devices operating with a load current of 100 mA during irradiation, the serial transistor's current gain declined steadily, while the base current increased continually. Figures 17 and 18 show the influence of annealing during the experiment, after a pause in irradiation, necessary for the voltage regulator's maximum output current to be examined. At these points (particularly at control points of 200 Gy, 300 Gy, and 400 Gy), slight decreases of the serial transistor's base current are observed as a consequence of a recovery caused by the termination of irradiation and the recombination of the trapped charge, due to higher currents and voltages used in our tests.

In contrast to the data presented for LM2940CT5 voltage regulators in tab. 2, the irradiated L4940V5 devices loaded with a 500 mA current had significantly different responses compared to the circuits used for examining the maximum output current, as can be seen in tab. 3. Voltage regulators L4940V5 have demonstrated much greater radiation hardness than their counterparts with lateral pnp transistors. The maximum output current remained close to the initial values detected before irradiation, being in the range of 780 mA to 860 mA [1]. Hence, the effects of increased recombination in the serial transistor's base area and, particularly the negative feedback loop reaction, had a greater impact on the forward emitter current gain. As previously reported, there was no sevenfold decrease of the forward emitter current gain (as the function of the base-to-emitter voltage, $\beta(V_{BE})$, in the entire operating area), but the negative feedback loop reaction, combined with the rapid increase of recombination in the serial transistor's base area, affected by its great perimeter-to-area ratio [1].

The measured and calculated values of the quiescent and base currents were much better for L4940V5 voltage regulators than for the LM2940CT5 devices. All of the examined samples of voltage regulators

Table 3. Change of the serial transistor's forward emitter current gain in voltage regulator L4940V5 as a function of the total ionizing dose. Current gain was determined during the examination of the maximum output current [1] and on-line monitoring of the irradiated devices' output and quiescent currents

Total dose, D [Gy]	β (I_{outmax}) [1]	β (on-line)
0	32.4	99.7
50	28.1	70.7
100	25.1	29.2
200	22.9	12.9
300	23.9	16.3
400	22.7	14.2
500	22.9	14.1

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L4940V5 had narrow variations of the unloaded circuit's quiescent current, between 3.75 mA and 3.81 mA. These minor variations enabled accurate data to be obtained, on the assumption of equivalence between the unloaded circuit's quiescent current and the internal consumption current for devices loaded with 100 mA and 500 mA. For the moderately loaded circuits, the mean base current has risen from 0.6 mA to 3.5 mA, while for the heavily loaded samples the assumed base current rose from 4.8 mA to 36.4 mA. The rising trend of the serial transistor's base current can be noted in figs. 17 and 18, indicating a steady increase in the moderately loaded device's base current.

As was mentioned in the analysis of the voltage regulator's maximum output current, the main reason for the radiation sensitivity of the examined vertical serial pnp transistor being higher than expected was the implementation of the interdigitated emitter [1]. An interdigitated emitter with very high perimeter-to-area ratio was applied in order to increase the emitter's injection efficiency during operation with high currents. Consequently, the positive oxide trapped charge had a great impact on emitter injection efficiency and spread of the space-charge region [1]. The spread of the space-charge region along the high-perimeter base-emitter contact increased recombination in the base area, affecting the rise of the serial power transistor's base current. After the initial rapid decrease, the forward emitter current gain remained in saturation for higher total doses. It may be seen from figs. 17 and 18 that both moderately and heavily loaded devices expressed a considerable rise of the base current, while the heavily loaded voltage regulators were more affected.

The pnp transistors are especially sensitive to the influence of interface traps on the degradation of the forward emitter current gain which is directly affected by the rise of the base current [22]. On the other hand, the positive oxide trapped charge above the base area suppresses the negative influence of interface traps, increasing the irradiated pnp transistor's radiation hardness [22]. During mentioned examinations of the low-dropout voltage regulator 29372, the rise in interface traps concentration was identified as the primary cause of the serial transistor's excess base current [6].

Apart from the expected influence of the interface traps and oxide trapped charge, the collector (load) current is another important parameter of the serial pnp transistor of the voltage regulator L4940V5. From figs. 17 and 18, it is obvious that the operation with a very high load current had a direct influence on the rise of the serial transistor's base current.

Seeing the previous discussion and characteristics of the base current in figs. 17 and 18, a hypothesis that radiation effects in the base area of the serial pnp transistor and in the isolation oxide above the base area had a dominant influence on the radiation response of the voltage regulator L4940V5 may be put forward. Oxide trapped charge generation in the two-layer oxide,

1000 nm thick [20], strongly suppressed the generation of interface traps in the initial phase of irradiation. An additional influence on the suppression of interface traps formation is to be attributed to the positive input bias voltage, which reduced interface traps concentration proportionally to the square root of the electric field intensity in the oxide [23]. Having the presented arguments in mind, it is justifiable to accept that the load current had a crucial influence on the base current through the recombination of the oxide trapped charge above the base area, reducing its positive effect on radiation hardness of the serial pnp transistor.

The operation of the heavily loaded samples of voltage regulators L4940V5 was analyzed before irradiation, as well as after the exposure. Since the input voltage of circuit L4940V5 was not stabilized, manifesting itself instead as a rectified line voltage, the heavily loaded voltage regulator L4940V5 did not have as good load regulation characteristics as was the case with moderately loaded devices. Therefore, even outside the radiation environment, slight variations of the output voltage were found to exist. Our measurements were performed on heavily loaded L4940V5 devices, in three-hour procedures equivalent to laboratory conditions shielded from radiation. Yet, measured variations of the output voltage in voltage regulators L4940V5 were much smaller, not exceeding 0.6% of the nominal value (about 30 mV). The exposure of the heavily loaded voltage regulators L4940V5 to γ-radiation certainly affected their load regulation characteristics, increasing the output voltage variations up to 2% of the nominal voltage. However, since during the entire time of irradiation the output voltage was above the threshold of 4.9 V (that is 2% less than the nominal voltage of 5 V), the operation of heavily loaded voltage regulators L4940V5 in radiation environment was acceptable. Even the most sensitive electronic device may tolerate variations of supply voltage up to 2% of its nominal value. As it was noted in previous articles [13, 14], voltage regulator L4940V5 is a radiation tolerant circuit, suitable for operation in a ^{60}Co environment for total deposited doses exceeding 500 Gy.

Although the data related to the serial transistor's forward emitter current gain and base current didn't have similar responses to those pertaining to maximum output current examinations, other tests of L4940V5 voltage regulators had analogous responses. This was particularly true of the examinations of the serial transistor's minimum dropout voltage [8] which validated the results of the on-line method of monitoring the serial pnp power transistor's base current and forward emitter current gain.

CONCLUSIONS

A novel method of on-line monitoring of the serial pnp transistor's base current and forward emitter

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current gain in voltage regulators has provided us with data from devices operating in a radiation environment without the need of interrupting their operation. With the data comprised of the voltage regulator's output voltage, output current and quiescent current, the operating status of the monitored device can be precisely determined. On the other hand, this method requires a referent, unloaded device placed inside the radiation field, used only to provide data on the quiescent current, necessary for calculating the properties of the other devices. Moreover, the input voltages of loaded and unloaded devices have to be approximated, which may complicate the measurement. This requires more unloaded referent devices if there are more loaded circuits with different input voltages.

Although the on-line monitoring method provided for the reliability of results in all examined cases, data obtained from the moderately loaded samples of LM2940CT5 voltage regulators pointed to the risks of considering results from the other sample to be approximately equal to original results. This assumption may be wrong, primarily when the serial transistor's base current is small compared to the internal circuit's consumption current. This indicates that the application of the on-line monitoring method is not recommendable for voltage regulators operating with loads lower than those of 10% of the nominal current. On the other hand, heavily loaded devices, operating with 50% of the nominal current, both in cases of lateral and vertical serial pnp transistors, gave reliable results.

However, our experiment indicated that on-line monitoring of the serial transistor's current gain and base current cannot be an absolute replacement for standard examinations of irradiated voltage regulators. It would still be necessary to perform standard experiments on test circuits and, only after the examined low-dropout voltage regulators have been approved, would it be possible to utilize on-line monitoring.

One of the main ideas of the proposed on-line monitoring method was its practical implementation, the monitoring of voltage regulators being a part of some more complex printed circuit boards operating in harsh conditions. The implementation of the on-line monitoring method would not demand significant changes in the construction of electronic devices used. Even extremely complex electronic boards would only need a few additional output contacts, particularly when the measurement of the voltage regulator's output voltage and current, as well as its quiescent current, are concerned. In addition, another unloaded referent voltage regulator would have to be added to the printed circuit board, supplied by the same input voltage as that of the main voltage regulator. Likewise, output contacts for the measurement of the output voltage and quiescent current of the referent device would have to be added, in order to enable the calculation of the serial transistor's base current in the loaded device. These minor modifications of the existing printed cir-

cuit boards for radiation-tolerant electronic equipment would enable remote on-line monitoring of their power supplies.

on-line monitoring of the serial transistor's current gain and base current can be successfully applied to the detection of the proper operation of low-dropout voltage regulators supplying electronic devices in radiation environments such as those surrounding nuclear reactors, accelerators and aerospace equipment.

The minimum load current of a low-dropout voltage regulator to which the on-line monitoring method could be applied (10% of the nominal load or those of a similar value) has to be experimentally obtained for each of the analyzed types and batches of the examined devices.

ACKNOWLEDGEMENT

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НЕПРЕКИДНИ НАДЗОР СТРУЈЕ БАЗЕ И КОЕФИЦИЈЕНТА СТРУЈНОГ ПОЈАЧАЊА РЕДНОГ ПНП ТРАНЗИСТОРА СТАБИЛИЗАТОРА НАПОНА У РАДИЈАЦИОНОМ ОКРУЖЕЊУ

Основна тема овог рада је развој методе за непрекидно праћење рада стабилизатора са ниским падом напона у радијационом окружењу. Захтевана метода треба да буде практична у експлоатацији, дајући могућност за детекцију деградације интегрисаног кола без прекидања његовог рада у пољу јонизујућег зрачења. Такође, треба да омогући аутоматизовано мерење и прикупљање података, као и детекцију значајне деградације знатно пре отказа надзираног стабилизатора напона. Основни параметри за праћење рада стабилизатора напона били су струја базе и коефицијент струјног појачања редног пнп транзистора. Ови параметри су добијени посредно, на основу података о струји потрошача и струји према маси стабилизатора напона. Као струја сопствене потрошње умерено и јако оптерећених узорака коришћена је струја према маси занемарљиво оптерећеног стабилизатора напона истог типа, употребљеног у својству референтне компоненте. Резултати добијени непрекидним надзором демонстрирали су значајну сагласност са резултатима добијеним испитивањем максималне излазне струје и минималног излазног напона стабилизатора напона у радијационом окружењу. Посебно сагласни резултати добијени су испитивањем јако оптерећених интегрисаних кола. У случају умерено оптерећених стабилизатора напона анализирани су добијени резултати, као и ризици примене представљене методе.

Кључне речи: коефицијент струјног појачања, струја базе, пнп транзистор, непрекидни надзор, струја сопствене потрошње, стабилизатор напона, гама зрачење