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Gamma-radiation response of isolated collector vertical PNP power transistor in moderately loaded voltage regulator L4940V5

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Radiation response of the serial isolated collector vertical pnp transistor in the voltage regulator L4940V5 is a complex function of the radiation-induced trapped charge concentration, load current, bias voltage and negative feedback reaction. Input bias voltage and oxide trapped charge above the base area improved radiation hardness of the serial transistor, whilst the load current and interface traps above the base decreased radiation tolerance of the examined devices. Additive radiation effects of interface traps and oxide trapped charge above the emitter area had a negative influence on radiation hardness of the serial pnp transistor. Negative feedback reaction heavily affected operation of voltage regulator L4940V5, causing a significant shift of the serial transistor's operating point on the characteristic $\beta(V_{BE})$. An analogy was perceived between characteristics of the serial transistor's base current in a moderately loaded voltage regulator L4940V5 and McLean's curves on variation of the interface traps concentration in a biased oxide.

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1. Introduction

During the previous two decades considerable attention has been devoted to the analysis of the total ionising dose and dose rate effects in linear voltage regulators [1]-[4]. These have been used extensively in radiation environments primarily due to their simple electronic circuitry, low price, reduced noise and rapid transient response to load conditions [5]. Voltage regulators were especially closely examined following the discovery of the enhanced low-dose-rate sensitivity (ELDRS), i.e., enhanced degradation of the exposed transistors in a low-dose-rate radiation environment, in comparison with operation in high-dose-rate radiation fields [6], [7]. Discovery of the ELDRS was especially important due to the use of electronic devices in aerospace applications. Aerospace electronic components are created for continuous operation in a low-dose-rate space environment for several years, or even decades. Due to the very high price of the specially designed radiation-hard integrated circuits, great attention was devoted to the use of radiation tolerant commercial off-the-shelf components.

In semiconductor devices, 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 an especial impact on the gain of bipolar transistors at low operating currents [8].

A device's susceptibility to radiation-induced charge production for a given dose depends strongly on its oxide layer quality. For bipolar transistors, 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 [8].

Early experiments performed on a low dropout voltage regulator, the "STMicroelectronics"® L4940V5, in gamma and X radiation fields led to surprisingly good results for the device's radiation hardness [9]. The relatively small degradation of the maximum output current and dropout voltage of this integrated circuit in radiation environments, for absorbed total ionising doses up to 3 kGy [9], indicated that the L4940V5 voltage regulator was a cheap commercial, off-the-shelf alternative to the specialised radiation-hard designs in moderate radiation environments. The main assumption was that the principal reason for its high radiation tolerance was the minor forward emitter current gain degradation of the serial isolated collector vertical pnp transistor [9]. However, further research on the BiCMOS voltage regulator L4940V5 with local isolation oxides pointed to a particularly high decline of the serial transistor's current gain, originating as a consequence of the very high perimeter-to-area ratio in an interdigitated serial transistor [10]. Therefore, increased recombination near the serial transistor's base-emitter contact led to the serious rise of the base current and consequently, initiated a rapid increase of the voltage regulator's quiescent current [10]. The measured decline of the vertical pnp transistor's forward emitter current gain had an even greater magnitude during the on-line examination of irradiated devices [11]. The results obtained led to the conclusion that a negative feedback loop affected the serial transistor's operation, forcing it to function with a much lower current gain [10,11].

During the examination of maximum output current it was noticed that bias conditions had a great influence on the measured values of the forward emitter current gain [10]. Also, after irradiation, even if the radiation tolerant low-dropout voltage regulator remained completely functional, if the serial transistor's dropout voltage significantly increased, it may be no longer suitable as a supply for battery powered devices due to the notably increased dissipation, or even a decrease in output voltage below the acceptable limit.

In this paper are presented results of further research of the radiation response of the low-dropout voltage regulator L4940V5. Various bias conditions and load currents were applied during the irradiation, followed by examination of the serial transistor's minimum dropout voltage, forward emitter current gain and base current.

2. Experiment

Integrated 5-volt positive commercial off-the-shelf voltage regulators (L4940V5) were tested in the Vinča Institute of Nuclear Sciences, Belgrade, Serbia, in Metrology - dosimetric laboratory. The L4940V5 devices were from the batch WKOOGO 408, made by "STMicroelectronics"® in China [9], [10].

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

The exposition doses measurement was performed with the cavity ionising chamber "Dosimentor"® PTW M23361, with a volume of $3 \cdot 10^{-5}$ m^3. With the cavity ionising chamber, the reader DI4 was used [10] and exposition doses were expressed in roentgens (R). Additional conversion into grays (Gy) absorbed in silicon-dioxide (SiO_2) was performed. Calculations were accomplished using the mass energy attenuation coefficients for air and SiO_2.

The samples of the L4940V5 voltage regulators were irradiated in groups of 4 circuits, until the predetermined total doses were reached. Devices in the γ-radiation field were exposed to a total dose of 500 Gy, with a dose rate of 4 cGy/s. The flat cables 10 m long supplied the devices. 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. Despite the fact that annealing begins immediately after the cessation of irradiation, this examination interval is considered completely acceptable. According to the most used standards for examination of total ionising dose effects (MIL-STD-883E Method 1019 and ESA-SCC 22900), the maximum time between irradiation and test is one hour [12], whilst the maximum time between two irradiations is two hours [12].

Current and voltage measurements were carried out with laboratory instruments; a "Fluke"® 8050A and a "Hewlett-Packard"® 3466A. Uncertainties of measurement for the specified instruments were 0.03% and 0.05%, respectively [13]. 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 uncertainty of measurement was used [13]. The calculated combined uncertainty of measurement for the implemented experimental procedure was approximately 0.6 % [13].

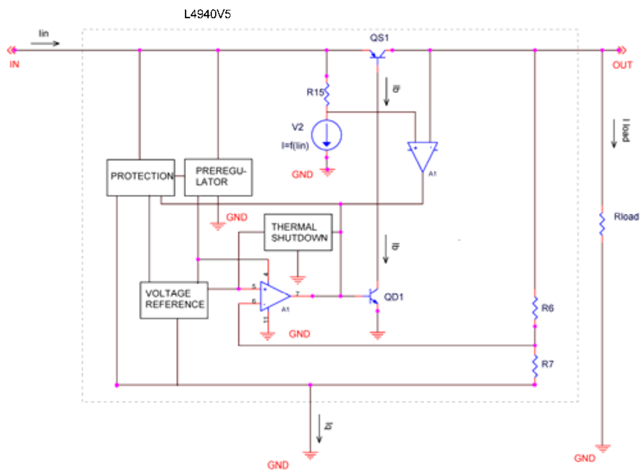

Fig. 1. Schematic block diagram of the voltage regulator "STMicroelectronics" L4940V5.

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

The examination of the change in minimum collector-emitter (dropout) voltage on the serial transistor was performed in the following way: input voltage was increased until output voltage dropped to 4.9 V, for the constant output current of 100 mA [9,14]. The difference between input and output voltage represents the dropout voltage on the serial transistor for corresponding current.

The next step was the measurement of output voltage and quiescent current for an unloaded voltage regulator with an input voltage, equal to the value measured on the device loaded with 100 mA, but as low as necessary to reduce the output voltage to 4.9 V. In voltage regulators with the serial pnp power transistor, a quiescent current (I_Q) represents a sum of control circuit's internal current consumption and a serial transistor's base current. The quiescent current of the unloaded voltage regulator (I_{Q0}) with a constant input voltage, was assumed to be approximate to the value of the loaded voltage regulator's internal consumption. The subtraction of the unloaded circuit's quiescent current from a quiescent current of devices loaded with 100 mA, for the same input voltages, gives a value of the serial transistor's base current [10], [11]:

$$I_b = I_q \Big|_{(I_C = I_{load})} - I_{q0} \Big|_{(I_C = 0)} \qquad (1)$$

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

Further details about the experiment and implemented technological process can be found in [9], [10], [15]. A detailed description of the L4940V5 integrated circuit is presented in [16].

3. Results

Figs. 2–7 present changes in the serial transistor's dropout voltage and forward emitter current gain for the "STMicroelectronics"® L4940V5 voltage regulators, for a constant load current of 100 mA and output voltage of 4.9 V. As the L4940V5 devices serial element is the vertical pnp power transistor, at first glance it was quite surprising that the measured values of the serial transistor's forward emitter current gain decreased by 30–80 times (Figures 3 and 4) [15]. This was particularly unexpected since this integrated circuit proved its radiation hardness during the previous examinations [9]-[11]! Despite the rise of up to 70% of the serial transistor's collector–emitter voltage (for the total dose of 500 Gy(SiO_2)), the absolute value of this voltage was not great (rise from 0.35–0.4 V to 0.5–0.65 V; Fig. 2) and the voltage regulator remained completely functional.

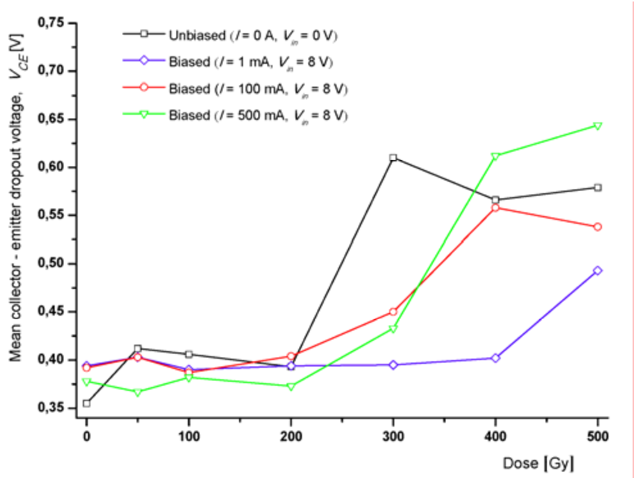

Fig. 2. Change in the mean serial transistor's minimum dropout voltage in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 100 mA).

These results led to the conclusion that a collapse of the forward emitter current gain was a consequence of the abrupt rise of the serial transistor's base current and operation with a low current of 100 mA during the examination. Together with the negative feedback loop reaction, this caused a significant shift of the voltage regulator's serial transistor's operating point toward the right part of the characteristic $\beta(V_{BE})$. A degradation of the serial vertical pnp transistor's forward emitter current gain of almost a hundredfold (for the constant values of the base-emitter voltage and for comparable values of the forward emitter current gain in the entire operating area) certainly did not occur.

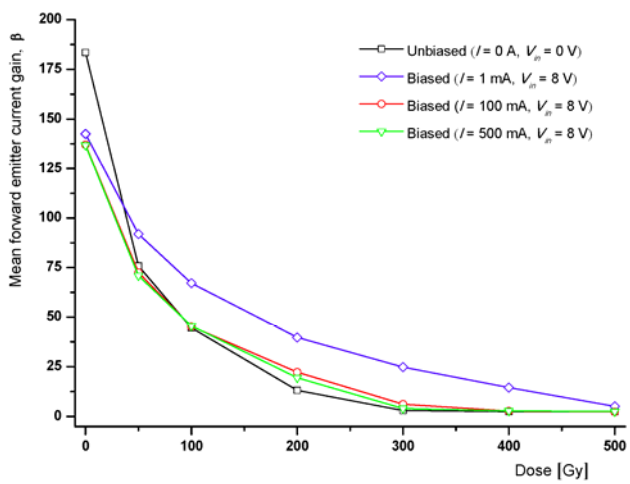

Fig. 3. Change in the mean serial transistor's forward emitter current gain in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 100 mA).

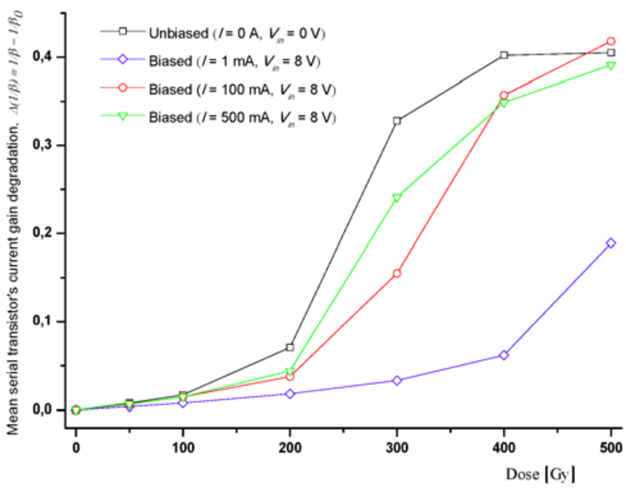

Fig. 4. Change in the mean serial transistor's current gain degradation in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 100 mA).

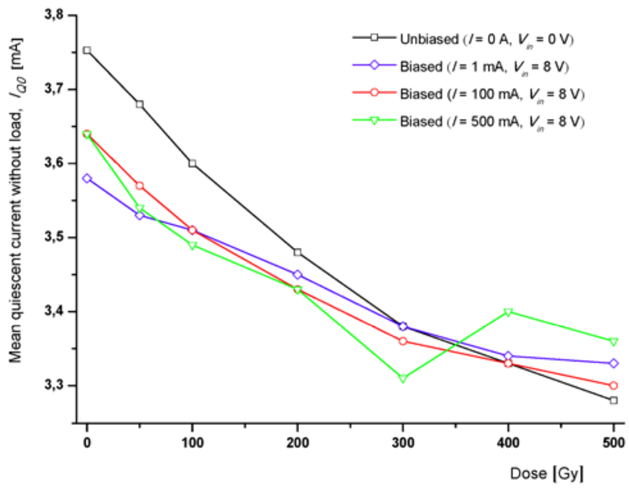

Fig. 6. Change in the mean quiescent current in the unloaded voltage regulator L4940V5 under the influence of γ-radiation ($V_{in} = V_{CE(100\,mA)}$ + 4.9 V, I_{out} = 0 A).

A large recombination of carriers in the base and emitter areas led to the rise of the base current up to 40 mA for the load current of 100 mA (Fig. 7). Values of the base currents presented in Fig. 7 were procured by the subtraction of the voltage regulator's quiescent currents without load (Fig. 6) from the total voltage regulator's quiescent currents (Fig. 5). Upon exposure to ionising radiation, positive charge accumulates in the oxide over the emitter-base junction. Positive oxide trapped charge repels holes in the p-type emitter and also accumulates in the base, resulting in the depletion region spreading into the emitter along the surface [17]. Depletion of the surface increases the recombination, which results in an excess base current [17].

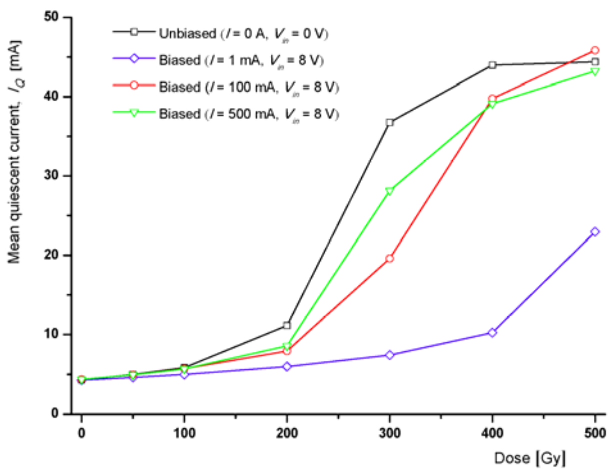

Fig. 5. Change in the mean quiescent current in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 100 mA).

Analysis of characteristics $\beta(D)$ and $V_{CE}(D)$ leads to the perception of a considerable difference in response between the biased samples with the negligible load current and other samples. In the case of biased devices with an input voltage of 8 V and an output current of 1 mA, load current can be neglected, because a current of 4 mA flows through the serial transistor of the L4940V5 voltage regulator towards the voltage divider, even in the cases when there is no connected load to the output terminal. The difference is particularly noticeable in the range of total doses between 200 Gy(SiO_2) and 400 Gy(SiO_2). A current flow through the n-type base causes the holes concentration to rise, affecting the increase of the base recombination.

Immediately after the beginning of irradiation the generation of the oxide and interface traps start [18]. A positive bias voltage, that is the increased electric field in the oxide, decreases the concentration of the interface states proportionally to the square root of the electric field intensity (for the electric fields exceeding 0.4 MV/cm) [19]. Yet, in a thick oxide (d_{ox} = 1080 nm), biased with 0 V and 5 V (conditions similar to those existing during the examination of the voltage regulator L4940V5), the concentration of interface traps was 50% greater in the biased oxide, compared with the irradiated oxide without an applied gate voltage [20]. Accordingly, the change of the interface traps concentration as a function of the electric field intensity in the oxide, cannot be straightforwardly described as in the case of high oxide fields. As the total thickness of the passivation oxide and phosphosilicate glass in the L4940V5 voltage regulator is about 1000 nm [9], for an input voltage of 8 V and base terminal voltage of nearly 5.6 V the electric field intensity in the oxide before irradiation would only be about 0.024 MV/cm. Nevertheless, regardless of the relationship with the applied electric field, the interface traps concentration steadily increases during the irradiation.

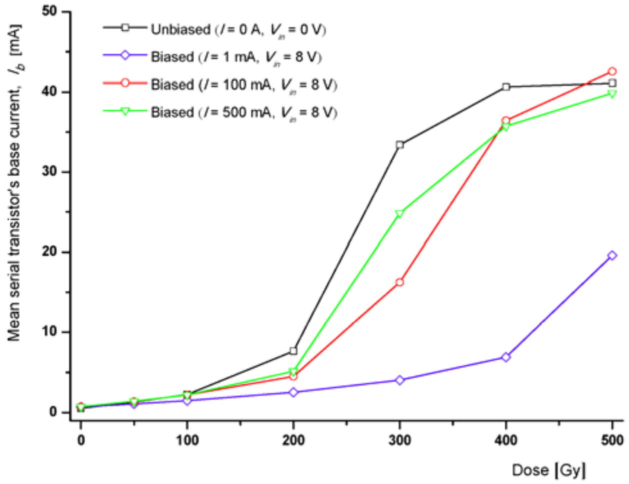

Fig. 7. Change of mean serial transistor's base current in the voltage regulator L4940V5 under the influence of γ-radiation (V_{out} = 4.9 V, I_{out} = 100 mA).

Fig. 7 is also a good illustration of the influence of trapped charge on a transistor's radiation hardness. Initially, changes of base currents were similar, regardless of the bias conditions, while after the absorption of a total dose of 200 Gy(SiO_2) significant differences emerged. At the point that represents a total dose of 300 Gy(SiO_2) in Fig. 7, it can be seen that the greatest increase of the base current was for unbiased circuits (V_{in} = 0 V, I = 0 A) and less for biased and heavily loaded devices (V_{in} = 8 V, I = 500 mA). An even smaller increase was noticed for moderately loaded circuits (V_{in} = 8 V, I = 100 mA) and the least increase of the serial transistor's base current was for biased and almost unloaded (V_{in} = 8 V, I = 1 mA) voltage regulators.

4. Discussion

The creation of interface traps is a consequence of the breaking of weak atomic bonds at the oxide-semiconductor interface, either by holes or by diffused hydrogen related species [21]. In references treating ELDRS in bipolar transistors, it was announced that pnp transistors are especially sensitive to the influence of interface traps on degradation of forward emitter current gain (i.e., a rise of the base current), opposite to that of npn transistors, which showed a greater susceptibility to the influence of the oxide trapped charge on a rise of the base current [22]. Also, in a weak electric field it was noticed that the rise of the interface traps concentration is proportional to the total ionising dose ($N_{it} \sim D$) [23].

Accordingly, application of an external electric field above the thick isolation oxide across the base area of the serial lateral pnp transistor would reduce the formation of interface traps, i.e., increase the radiation hardness of the irradiated voltage regulator. On the other hand, in a vertical pnp transistor the main current flow is not located in the vicinity of the isolation oxide (having an impact on the concentration reduction of the oxide trapped charge), but in deeper layers of the wafer [9]. Therefore, a positive influence of the oxide trapped charge on suppression of the negative influence of interface traps on the serial transistor's base current would be seriously minimised. It should be pointed out that oxide trapped charge can be positive (oxide trapped holes) and negative (oxide trapped electrons), but the former are more important, as the hole trapping centres are more numerous [18, 24].

During previous examination of a "Micrel"® MIC29372 low-dropout voltage regulator [25], [26], authors have noticed that the greatest degradation in the gamma radiation field was endured by unbiased devices, whilst a smaller degradation was perceived on samples operating with bias voltage. A rise of the interface traps concentration (N_{it}) was identified as the primary cause for the rise of the serial transistor's base current [25].

In addition to the expected influence of the interface traps and oxide trapped charge, collector (load) current is another important parameter that has influence on the variation of the serial transistor's base current and forward emitter current gain in the L4940V5 voltage regulator. From Fig. 7 it can be seen that the rise of the load current has a direct influence on the rise of the serial transistor's base current, i.e., a reduction of its radiation tolerance. Another important detail is the interesting similarity of the base current curves in Fig. 7 with the well-known McLean's diagram on the change of concentration of interface traps in SiO_2 with various gate bias conditions (permanent positive and negative gate voltage, also a switching of gate voltage from negative to positive after 1 s, 25 s and 200 s; Fig. 17 in [27]).

There have been many conflicting models proposed to describe the process by which radiation produces interface traps [27]. All the models are consistent with the idea that the precursor of the radiation-induced interface trap is a Si atom bonded to three other Si atoms and a hydrogen atom [27]. When the Si–H bond is broken, the Si is left with an unpassivated dangling bond, as an electrically active defect. The dominant process is a two-stage process involving hopping transport of protons, originally described by McLean [27]. In the first stage of this process, radiation-induced holes transport through the oxide, and free hydrogen, in the form of protons. In the second stage, the protons undergo hopping transport. When the protons reach the interface, they react, breaking the SiH bonds already there, forming H and a trivalent Si defect [27].

One of the critical experimental results is shown in Fig. 17 (in [27]), which shows the results of bias switching experiments. For curve A, the sample was irradiated under positive bias, which was maintained throughout the experiment, and a large interface trap density eventually resulted [27]. For curve B, the bias was negative during irradiation and hole transport, so the holes were pushed away from the interface, but the bias was switched positive after 1 s, during the proton transport. The final number of interface states for curves A and B is almost the same, however [27]. For curve E, the bias is maintained negative throughout both stages, and interface trap production is suppressed completely [27]. For curves C and D, the bias is negative during irradiation and hole transport, but switched positive later than for curve B [27]. In all cases, bias polarity during the hole generation and transport made no difference, but positive bias during the proton transport was necessary to move the protons to the Si-SiO_2 interface. The time scale of the interface trap buildup was determined by the transport time of the protons [27]. For curves B, C, and D, the protons were initially pushed away from the interface, so it took them longer to get there after the proper bias was applied [27].

McLean's curves for a completely positive gate voltage are dual to the characteristic of unbiased voltage regulator (although with a rising trend of the interface traps concentration immediately after the start of irradiation). Likewise, McLean's curves for the transition from a negative to a positive gate voltage are dual to the curves of base currents for serial transistors with input voltage and various irradiation currents.

An analogy between these two occurrences can be inferred; a decrease of load current during the irradiation had an analogous effect on the fall of the serial pnp transistor's base current, as had a protracted duration of negative gate voltage on the reduction of the interface traps concentration in the oxide. The higher the serial pnp transistor's load current, the faster the rise of the serial transistor's base current and lower its radiation hardness.

However, it is necessary to evaluate each mechanism that may affect the increase of the serial pnp transistor's base current. Therefore, it requires some data related with the construction of the serial pnp transistor. Implemented pass element is the isolated collector pnp power transistor (ICV PNP) [28], created from 36 groups of elementary interdigitated pnp transistors made by "HDS^2/P^2"® Multipower 20 V ("High Density Super Signal / Power Process") [9], [29]. A vertical pnp transistor is created with the isolated collector (graded collector with p enhancement region, with total quantity of boron impurities per unit area $Q_B \approx 5{\cdot}10^{13}$ cm^{-2} and p- area, dopant was boron, $Q_B \approx 10^{13}$ cm^{-2}) and the nested emitter (p-type, with phosphorous impurities, $Q_P \approx 5{\cdot}10^{13}$ cm^{-2}). Also, graded base was implemented (n+ area near the base contact, with arsenic impurities, $Q_{As} \approx 5{\cdot}10^{15}$ cm^{-2}, together with the n-type volume of base surrounding the emitter, with boron impurities, $Q_B \approx 2{\cdot}10^{13}$ cm^{-2}) [9], [29]. The depth of the epitaxially grown layer used for the construction of the active elements is around 10 μm [9], [29]. After completed synthesis of the semiconductor structure, an insulating layer made of SiO_2 is deposited above the wafer, followed by another layer of SiO_2 implanted with phosphorous and boron (Phosphorous Boron Silicon Glass, PBSG). Both layers have a thickness of 500 nm [9], [29].

For the exact determination of the doping densities of the emitter, base and collector, it would be necessary to obtain exact data on the effective width of their layers. However, those data are not provided in the examined references [28], [29]. It is only certain that the vertical dimension of the collector is approximately 10 μm (depth of n- type epitaxially grown layer). However, data on breakdown voltages ($BV_{CE0} \geq 20$ V, $BV_{CB0} \geq 60$ V) and some examples from the literature on high–voltage bipolar integrated-circuit fabrication ($N_C = 10^{15}$ cm^{-3} for $BV_{CE0} =$ 36 V and $BV_{CB0} = 90$ V) [30] may lead to a useful approximation.

The base width can be estimated from the gain–bandwidth product, f_T (product of the common emitter current gain β and the frequency of measurement at which the gain-frequency curve begins to descend) [12]. As the gain–bandwidth product for ICV PNP transistor is $f_T = 80$ MHz [28], from the table for calculation of a base width from approximate gain–bandwidth product in [12], the active base width may be estimated as approximately 2.25 μm. If the effective emitter length was rated on 1.5 μm, and also according to the known initial values of total quantity of impurities per unit area in emitter and active base area ($Q_P \approx 5{\cdot}10^{13}$ cm^{-2} and $Q_B \approx 2{\cdot}10^{13}$ cm^{-2}), rated surface doping densities in the emitter and active base area are $3.3{\cdot}10^{17}$ cm^{-3} and $9{\cdot}10^{16}$ cm^{-3}, respectively.

According to the presented data and geometry of the isolated collector vertical pnp transistors [9], [28], its response is very complex. Basic mechanisms for the degradation of pnp transistors in radiation environments are the depletion of the p-type emitter, recombination at the base surface, electron injection into the emitter and surface hole depletion [17].

Regarding the interdigitated emitter-base junction, occupying two thirds of the entire chip area [28], it is clear that depletion of the p-type emitter due to the oxide trapped charge may be an important mechanism for rise of the serial pnp transistor's base current. However, due to the relatively high impurity concentrations (for a power bipolar transistor) in a range of 10^{17} cm^{-3}, it could not be expected that the emitter depletion would be the primary cause of the excess base current.

As the emitter was not heavily implanted, compared with the base area, mechanisms of electron injection into the emitter and the surface holes depletion would have an influence on serial transistor's forward emitter current gain. Enhanced electron injection into the emitter is manifested through the accumulation on the surface of the base, caused by the positive charge trapped in the oxide over the emitter-base junction. When a forward bias is applied to the junction, more electrons may be injected into the emitter, resulting in the excess base current [17].

The surface holes depletion mechanism is related to the path followed by the holes injected into the base. Nevertheless, since the main current flow in vertical pnp transistors is far away from the oxide surface, it is a valid presumption that influence of this mechanism on degradation of the serial transistor's forward emitter current gain may be neglected.

The final mechanism to be discussed is the increased recombination at the n-type base surface. In this case interface traps increase the current gain degradation. The interface traps cause an increase in the recombination velocity along the base surface [17]. However, the positive oxide trapped charge accumulates at the base surface, leading to a condition of a relatively low recombination rate at the surface, as recombination is at a maximum when the electron and hole magnitude is equal. Thus, the interface traps formation and the oxide trapped charge above the base area, are competing effects [17].

The influence of increased surface recombination may be the most difficult to evaluate, as the nested emitter is surrounded by the graded base. From the one side, where the base electrode contact is situated, there exists a heavily doped small n+ area, preventing significant surface radiation effects in the vicinity. Yet, on the other side of the nested emitter is a moderately doped basic n-type base area (Fig. 1 in [9]). As the moderately phosphorous doped n-type layer represents the bulk of the base area, favourable conditions exist for the generation of interface traps above this section of the pnp power transistor. Due to the two-layer, 1000 nm thick isolation oxide above the surface of the wafer, high concentrations of the oxide trapped charge may be expected in the radiation environment.

The emitter of the vertical pnp transistor is not as heavily implanted as expected (nearly four times more than the basic volume of the phosphorous-implanted n-type base; heavily-doped arsenic-implanted n+ area near the base contact serves only for the reduction of the series base resistance). However, initial impurity concentrations of four times higher will secure significantly less spread of the depletion region than in the emitter area, but a radiation-induced degradation of the emitter could not be neglected.

From the previous theoretical discussion and characteristics of the base current in Fig. 7, it may be reasonable to surmise that radiation effects in the base area of the serial transistor and in the isolation oxide above the base had the dominant influence on radiation response of the vertical pnp transistor. Contrary to the presumption that surface recombination processes would have a negligible effect on the vertical pnp transistor [17], it seems that the generation of interface traps on the surface of the base area caused a considerable spread of the depletion region in the base area, influencing the rise of the base current. However, 1000 nm thick two-layer oxide, with one heavily contaminated layer (PBSG), strongly suppressed the generation of interface traps in the initial phase of irradiation (for total doses lower than 200 Gy(SiO_2)).

Additional influence on the interface traps formation had a positive input bias voltage. However, beside the trapped charge in various areas Fig. 7 shows, as mentioned earlier, the strong influence of load current on radiation response of the vertical pnp transistor. From the presented arguments, it is justifiable to accept that the load current had the major influence on the base current through the recombination of the oxide trapped charge above the base area, reducing its positive effect on the radiation hardness of the serial pnp transistor.

The operation of biased samples with input voltage and negligible load, expressed the best performance due to the suppression of the interface traps formation caused by the electric field in the oxide above the base area, being the mutual effect of the oxide trapped charge and implemented input voltage. As the load current during the irradiation increased, the greater number of the positive carriers in the oxide recombined with electrons from the current flow, reducing its positive influence on accumulation of the base surface and consequently, leading to the spread of the depletion region in the base area as the primary cause of the excess base current.

The unbiased samples demonstrated slightly higher radiation susceptibility than heavily loaded biased devices. The main reason for this was the absence of the input bias voltage, leaving only the defects in the oxide to affect the formation of the interface traps.

Due to the higher doping concentration of the emitter area, emitter depletion had less influence on the rise of the excess base current. Yet, owing to the moderate difference in doping concentrations between the base and emitter areas (approximately four times) and interdigitated geometry of the base–emitter junction, the spread of the depletion region in the emitter area is not a negligible effect. Emitter depletion, together with the electron injection into the emitter, are secondary mechanisms affecting the rise of the vertical pnp transistor's base current.

Surface holes depletion did not have a significant effect on excess base current, as the effective base area is located below the emitter area, far away from the isolation oxide.

In short, interface traps and oxide trapped charge above the base area, together with bias voltage and load current had the major influence on the base current of the serial vertical pnp transistor in the L4940V5 voltage regulator. When devices were unbiased, i.e., without suppression of the interface traps by the external electric field, the rise of the interface traps concentration was greatest, causing (combined with the negative feedback reaction) the fastest rise of the base current. Vice versa, implementation of the input voltage with a negligible load highly suppressed the formation of the interface traps and, together with the electric field generated by the oxide trapped charge above the base, caused the slowest rise of the base current. Between these two extremes were bias conditions with moderately loaded (100 mA) and heavily loaded (500 mA) L4940V5 voltage regulators and the rise of the load current decreased the influence of the oxide trapped charge, i.e., it affected the faster rise of the base current.

Finally, the effects of the local oxide on radiation hardness of L49490V5 voltage regulators have to be analysed. Digital circuits are usually designed to be relatively insensitive to variations in current gain, so total-dose failures in digital ICs are primarily isolation-related [31]. However, for most bipolar technologies that are used in linear integrated circuits, the total-dose failure mechanism is reduction of the current gain [31]. Voltage regulators L4940V5 have passed extensive radiation tolerance examinations in previous years [9]-[11]. Samples were tested in various radiation environments and with a wide range of bias voltages and load currents. However, none of the examined circuits demonstrated failures related to establishment of radiation-induced leakage currents, regardless of the presence of local oxides in integrated circuits. Vertical pnp transistors are usually radiation tolerant because the net positive charge in the oxide accumulates the base region. Since the emitter doping in vertical pnp transistors is large compared to the base doping in npn transistors, the effects of oxide charge on surface recombination are much less. Also, application of the isolated collector in vertical pnp transistors improved radiation tolerance of L4940V5 voltage regulators, since in this way establishment of radiation-induced leakage current between collector and emitter of a vertical pnp transistor is not possible.

None of the examined samples of L4940V5 voltage regulators showed output voltage to fall below the threshold of 4.9V, nor an excessive change of the serial transistor's dropout voltage.

5. Conclusion

The results obtained for the proven radiation hard L4940V5 voltage regulators, were partially unexpected. Dropout voltage on serial transistors increased up to 70%, whilst the observed decrease of the forward emitter current gain was by 30–80 times. The great decrease of the forward emitter current gain in the L4940V5 voltage regulator was the consequence of the abrupt rise of the serial transistor's base current and operation with a low current of 100 mA during the examination. Altogether, with the negative feedback loop reaction this caused a significant shift of the voltage regulator's serial transistor's operating point on the characteristic $\beta(V_{BE})$, and not the almost hundredfold degradation of the forward emitter current gain for a constant base–emitter voltage.

Although relatively significant, the rise of the minimum dropout voltage on the serial vertical pnp transistor was not great in absolute values (reaching 0.65 V) and it would not endanger a proper operation of the voltage regulator with a battery supply. Despite the vertical current flow, interface traps demonstrated a much higher influence on the operation of the L4940V5 voltage regulator than was expected. The response of the serial ICV PNP power transistor was a complex function of the radiation-induced trapped charge concentration, load current and bias voltage. The input bias voltage and oxide trapped charge above the base area improved the radiation hardness of the serial transistor, whilst the load current and interface traps above the base had a significant negative influence. The additive radiation effects of interface traps and oxide trapped charge above the emitter area expressed a negative influence on the radiation hardness of the serial pnp transistor, but owing to the higher doping concentration in the emitter area, they had secondary influence on its excess base current. A negative feedback reaction showed a greater influence on variations of measured values of the serial transistor's forward emitter current gain than interface traps and the oxide trapped charge, causing the great shift of the voltage regulator's operating point on characteristic $\beta(V_{BE})$. An interesting analogy was inferred between characteristics of the serial transistor's base current (combined influence of radiation induced trapped charge, bias voltage, load current and negative feedback reaction) in the moderately loaded L4940V5 voltage regulator and McLean's curves on the variation of the interface traps concentration in a biased oxide.

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