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Total ionizing dose degradation of power bipolar integrated circuit

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Variations of ionizing dose response in terms of various types of radiation and bias conditions were presented for voltage regulator produced in "National Semiconductor" bipolar process. Technological realization of monolithic integrated circuit, also as its impact on device's degradation were shown. Manifestations of surface recombination mechanisms in semiconductor and positive charge trapping in oxide were presented. Changes of serial transistor's maximum collector current, collector - emitter dropout voltage, output voltage and load regulation characteristics were presented for voltage regulators from two batches made by the same manufacturer. Examined samples showed severe characteristics degradation even at low and medium total ionizing dose levels, indicating low radiation hardness of "National Semiconductor" bipolar process. Devices from various lots showed significant differences in radiation response.

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Keywords: Ionizing radiation, Bipolar process, Lateral transistor, Surface recombination, Voltage regulator

1. Introduction

Although in fabrication of modern integrated circuits dominate technologies based on MOS transistors, integrated circuits found on bipolar transistors are still widely spread, in particular among the special applications, where are necessary high transistor current density and radiation hardness. Research topic presented in this paper is characteristics examination of "National Semiconductor" bipolar process for synthesis of monolithic analog integrated circuits after exposure to medium dose rate X and γ radiation, i.e. low and medium energy photons. Representative of linear integrated circuits designed with "National Semiconductor" (NS) bipolar process is low-dropout voltage regulator LM2940CT5 with lateral power PNP transistor. Among the vertical NPN transistors, important characteristic of NS bipolar design is possibility of lateral PNP transistors synthesis, including power transistors for currents exceeding 1 ampere [1]. Thus voltage regulator LM 2940CT5 represents medium scale integration device with vertical NPN and lateral PNP transistors, JFET transistors, also as PNP lateral power transistor. According to the assumed radiation softness of lateral PNP transistors, it is supposed that the power PNP transistor would be the weakest point of the circuit in terms of radiation hardness. Due to construction of power transistor, comprised of 350 parallel connected PNP transistors [2], obtaining the maximum output current of 1 ampere, it may be surmised that such large number of parallel elements may provide higher redundancy, i.e. radiation hardness of pass transistor and entire NS bipolar process. Also, small perimeter-to-area ratio of NS bipolar process power PNP transistor [1] makes it a candidate for higher radiation hardness, since the increase in the normalized base current and surface area depletion is directly proportional to the perimeter-to-area ratio.

Some authors consider PNP devices to be harder than NPN devices because the N-type base is not depleted and the P-type emitter is very heavily doped, requiring very large densities of positive oxide charge to deplete the surface. In addition, the interface traps tend to be concentrated over the emitter side of the junction by the fringing electric fields [3].

Mentioned reasons make the "National Semiconductor" bipolar commercial process and its representative LM2940CT5 a serious candidate for significant radiation hardness and use in nuclear reactor and high-energy physics systems. Maximum load current, serial transistor collector - emitter dropout voltage and load regulation characteristics of LM2940CT5 low dropout voltage regulator were tested, without bias and with input voltage and load current. Integrated circuits from two batches of the same manufacturer were examined.

2. Theory

2.1. Radiation response of lateral PNP bipolar transistors

Ionization-induced gain degradation in the NPN transistors has been shown to be owing to the increased recombination in the emitter-base depletion region. Increase in recombination is due to two mechanisms: increase in surface recombination velocity, caused by the interface states near midgap, and silicon surface depletion, caused by the increase of the surface potential, induced by the trapped charge in oxide. Areas of positive trapped oxide charge and interface traps are shown in Fig. 1. The

excess base current increases rapidly as a function of the net charge in the oxide and thus the oxide charge tends to dominate the radiation response [4].

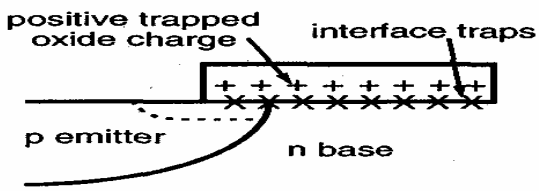

Fig. 1. Positive trapped oxide charge and interface traps in lateral PNP transistor [4].

Due to lower common emitter current gain and lower operating frequency, PNP transistors are more sensitive to ionizing radiation exposure than NPN transistors [5]. Owing to the surface recombination mechanism, influence of ionizing radiation is more expressed with lateral transistors, having current flow right under the oxide layer, in comparison with vertical substrate transistors, where current flows through the semiconductor bulk [6]. However, technological realization of the lateral transistor is much simpler and the current gain is also slightly higher than for the vertical substrate transistor.

Four possible mechanisms may cause current gain degradation of PNP transistors. They are: 1. depletion of the P-type emitter; 2. recombination at the base surface; 3. electron injection into the emitter and 4. surface hole depletion [4].

Upon the exposure to ionizing radiation, positive charge accumulates in the oxide over the emitter-base junction. The trapped positive oxide charge repels holes in the P-type emitter and also accumulates the base, resulting in the depletion region spreading into the emitter along the surface. The depletion of the surface increases the recombination, which results in an excess base current [4].

In the case of increased recombination at the N-type base surface, interface traps increase the current gain degradation. The interface traps cause the recombination velocity along the base surface to increase. Trapped positive oxide charge accumulates the base surface leading to a decrease of recombination rate at the surface [4]. Based on Shockley-Read-Hall (SRH) recombination theory, the recombination rate at the surface can be written as a function of lateral position, y, as [7]:

$$R_S(y) = \frac{n_i v_{surf} \exp\left(\frac{qV_{BE}}{2kT}\right)}{2\cosh\left[\frac{q}{kT}\left(\psi_S(y) - \frac{V_{BE}}{2}\right)\right]} \quad (1)$$

In this equation, n_i is the intrinsic carrier concentration, ψ_S is the surface potential and V_{BE} is base-emitter voltage of bipolar transistor. The surface recombination velocity is given by $v_{surf} = \sigma v_{th} N_T$, where σ is the capture cross section, v_{th} is the thermal carrier velocity, and N_T is the trap density.

Positive oxide charge trapped in the oxide over the emitter-base junction accumulates the surface of the base. Accumulation of the base locally converts the emitter-base junction from a P+-N junction to a P+-N+ junction. Since the base is accumulated, many electrons may be injected into the emitter, resulting in excess base current [4].

The surface hole depletion mechanism is related to the path followed by the holes injected into the base. As positive oxide charge increases, holes are driven away from the surface. As the holes are forced deeper into the structure, the path that the holes must travel to reach the collector becomes longer, in effect making the base appear longer. The recombination rate increases due to the holes traveling toward the n+ buried layer. The surface mechanisms, such as recombination at the base surface and surface hole depletion, play much more significant roles in the lateral devices [4].

Degradation of the lateral device is dependent upon the emitter doping. Lateral PNP transistors with heavily doped emitters have higher initial current gain and also are less sensitive to ionizing radiation. A lightly doped emitter allows greater expansion of the depletion region into the emitter and the resulting excess recombination outweighs moderation of the increase due to positive oxide charge [8]. This is because oxide trapped charge increases recombination in the emitter of the lightly doped devices, causing the base current to increase more rapidly than it does in the heavily doped devices [9].

Beside the increase in excess base current, in lateral PNP transistors a slight decrease in collector current also contributes to current gain degradation. Collector current changes significantly with total dose. Since the base current increases at low total doses, reduction of collector current has a strong impact on gain degradation. The decrease in the collector current of the heavily doped emitter devices is due to two effects: recombination in the neutral base region and reduction of emitter injection efficiency [9].

Increased recombination in the emitter-base depletion region does not reduce the collector current at a given bias level because the number of carriers injected into the base depends only on the doping of the base and the applied bias. If recombination increases in the depletion region, the emitter and base currents increase, but the collector current remains constant. However, when injected carriers recombine in the neutral base, they do not reach the collector junction and the collector current decreases. Since the total current depends strongly on carriers injected near the surface, this results in a significant drop in the collector current as the devices are irradiated. This effect leads to a reduction in emitter injection efficiency [9]. Emitter injection efficiency increases with decrease of base width and increase of perimeter-to-area ratio. High perimeter-to-area ratio enables reduction of base spreading resistance and, consequently, emitter crowding, but makes transistors very susceptible to degradation due to ionizing radiation exposure, mainly owing to the large area of base - emitter junction.

A portion of reduced collector current may be attributed to recombination in the neutral base. Reduced

collector current due to neutral base recombination causes the base current to increase while leaving the emitter current constant [9].

For the constant base current, increase in collector - emitter voltage induces decrease of base width and, subsequently, increase of collector current I_C. Relation for the transistor collector current in the forward active region seeing the Early effect may be written as [5]:

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

where is: q - charge of electron, A - cross sectional area, D_p - hole diffusion coefficient, W_B - base width, N_D - donnor concentration, V_{CE} - collector - emitter voltage, V_A - Early voltage, $V_T = \frac{kT}{q}$ - thermal voltage.

2.2. Characteristics of implemented bipolar process

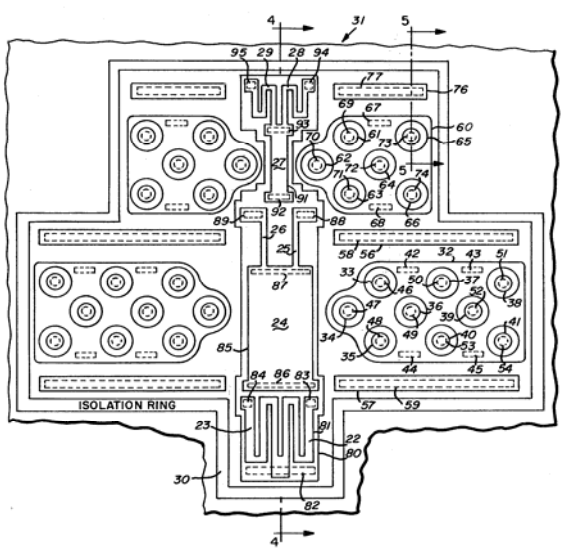

Fig. 2. Topology of the lateral PNP power transistor [1].

Voltage regulator "National Semiconductor" LM2940CT5 is an analog integrated circuit created with conventional process for synthesis of monolithic-silicon junction-isolated integrated circuits [10]. The main area of the chip is occupied with PNP pass transistor and its driver transistor. Serial PNP transistor consists of 350 parallel connected PNP transistors and enables maximum output current of about 1050 mA for β = 15-20, with quiescent current 50 - 60 mA [1], [2]. Each transistor may obtain current 3 mA and greater current capacity is achieved by their parallel connection in structures with ballasting resistors. For applied bipolar process, values for a single PNP transistor are: β = 24 (for I = 1 mA), BV_{CB0} = 94V (breakdown voltage collector - emitter with base open), f_T = 2.5 MHz (maximum frequency) [10]. Pass PNP transistor consists of smaller groups comprising 18 and 24 basic PNP transistors, where the major group of 24 transistors is closer to the input base terminal, while the minor group is situated between collector and emitter pads. Area of PNP power transistor is about 2.4 mm^2, while the area of PNP driver transistor, comprising of 70 basic PNP transistors is about 0.5 mm^2, altogether occupying about two thirds of the chip area [1].

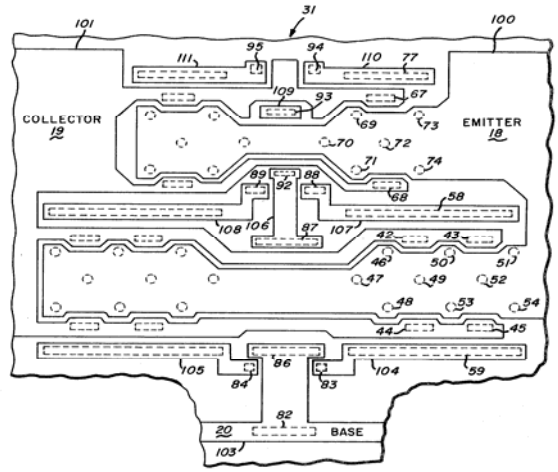

Fig. 3. Metalization of the lateral PNP power transistor [1].

Layout of PNP power transistor and metalization areas are shown in Figures 2 and 3, while the cross sections (areas 4 and 5 in Fig. 2) are shown in figures 4 and 5 [1]. In Fig. 2 transistors are grouped in sections of six and nine elements, divided with ballast resistor. Emitters are round, approximately 13 μm in diameter. Between emitters and collector diffusion region are base rings, belonging to the N type epitaxial layer [1]. Cross section of a single lateral PNP transistor is shown in Fig. 6.

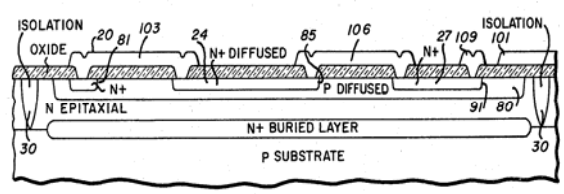

Fig. 4. Cross section of the Fig. 2 structure taken through the central region [1].

Fabrication of integrated circuit in "National Semiconductor" bipolar process begins with wafer 400 - 500 μm thick and with resistivity 4 Ω·cm. Thickness of N epitaxial layer is 15 μm, diffused with arsenic (As) impurities having concentration 10^{15} cm^{-3}. Under the epi - layer is highly doped N+ buried layer (Fig. 7) with conductivity 20 Ω/□, created with slowly diffusing arsenic (As) impurities [11]. Isolation from the other transistors is performed by the P+ isolation ring, boron diffused through the epitaxial layer. On the epitaxial layer are realized P+ emitter and collector regions by boron diffusion 3 μm in depth, with atoms surface concentration $2\cdot10^{18}$ cm^{-3}. In final is executed the step generation of passivation layers, creating SiO_2 oxide layer about 500 nm thick [10]. Beside

the creation of lateral PNP transistors, NS bipolar process enables realization of NPN vertical transistors, also as JFET transistors using the same production steps. Like the realization of P+ regions for collectors and emitters of lateral transistors with 3 μm boron diffusion, in the same step is possible realization of NPN transistor base, also as N-channel JFET drain and source. Collector and emitter of NPN transistor, base of PNP lateral transistor and JFET gate are created by the phosphorus (P) diffusion 2 μm in depth and with impurities concentration 10^{19} cm^{-3} [11].

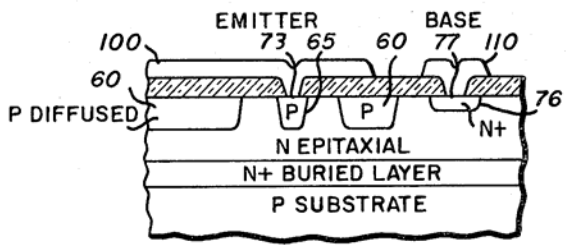

Fig. 5. Cross section of a single transistor from the Fig. 2 [1].

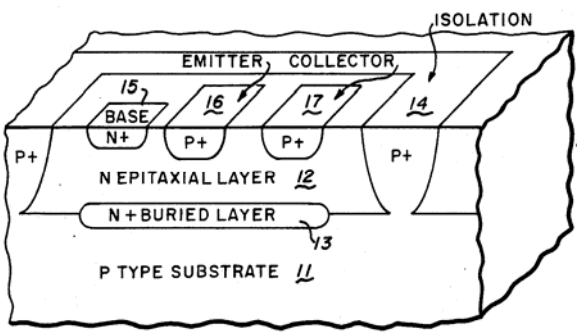

Fig. 6. Cross section of a lateral PNP transistor[10].

3. Experiment

Integrated 5-volt positive voltage regulators "National Semiconductor" L2940CT5 were tested in Institute of Nuclear Sciences "Vinča", Belgrade, in Metrology - dosimetric laboratory. Twenty integrated circuits were separated in four groups. Five unbiased IC's were tested on sources of γ and X radiation each. Next two groups of five voltage regulators were tested with bias and load during the irradiation. In this case input voltage was 7V, while output current was kept on 100 mA [12]. Another ten unbiased IC's from the other batch of the same manufacturer were exposed to γ and X radiation.

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

For the purpose of obtaining X radiation, that is photons spectrum of mean energy 150 keV, dosimetric generator PHILIPS MG 320 was used. Voltage and current of the roentgen tube MC 321 were set to 300 kV, 10 mA during the experiment. Target material was tungsten and the basic filtration was performed with 4 mm aluminium foil. Additional filtration was performed with 0.47 mm thick aluminium foil.

Exposition doses measurement was exerted with the cavity ionizing chamber "Dosimentor" PTW M23361, volume 3×10^{-5} m^3, with uncertainty of measurement ± 2%. With cavity ionizing chamber, reader DI4 was used [13].

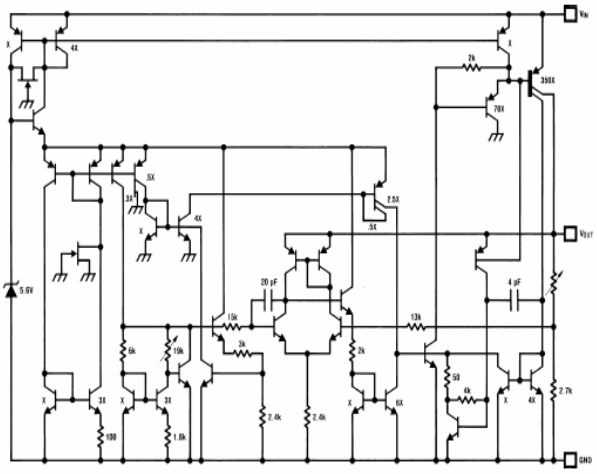

Fig. 7. Circuit diagram of the voltage regulator LM2940CT5 [2].

Samples of voltage regulators LM2940CT5 were irradiated in groups of two circuits. Ten meters long cables supplied devices. To keep the operation stability and suppress the noise, on IC's input contacts, 33 μF electrolytic capacitors were mounted. At the ends of power supply cables, on the circuits' outputs were mounted additional 47 μF electrolytic capacitors to obtain the output voltage stability. Beside the supply cables were laid sense cables of the same length. All measurements and the irradiation of components were performed on room temperature of 19^0C.

Macroscopic values used for the detection of voltage regulator's degradation due to exposure to ionizing radiation were maximum serial transistor collector current (load current), serial transistor collector - emitter dropout voltage and change of collector (output) voltage. Examination of maximum collector current change was performed in the following way: for constant input voltage equal to 8 V, load current was increased until output voltage dropped to 4.7 V. Lower output voltages are unacceptable for voltage regulator, since the device is beginning to shutdown [14].

Examination of collector - emitter dropout voltage change on serial transistor was performed in the following way: input voltage was increased until output voltage dropped to 4.9V, for constant output current of 100 mA. Difference between input and output voltage represents dropout voltage on serial transistor for corresponding current. Owing to the decrease of transistor common emitter current gain after exposure to ionizing radiation, output voltage value used to fall below 4.9V; therefore, in

order to acquire complete data regarding device functioning ability after irradiation, it is also necessary to obtain information about the change of maximum output voltage as a function of total ionizing doze (TID).

During the load regulation characteristics examinations, after the corresponding irradiation period, values of output voltage were measured for constant input voltage (6.5V, 8V, 10V, 12V and 15V), while the output current was varied (0A, 100 mA, 300 mA, 500 mA and 700 mA). Obtained diagrams represent the difference between output voltage of unirradiated circuits and output voltage of components exposed to total ionizing dose (TID) 300 Gy(Si) in γ radiation field, i. e. 600 Gy(Si) in X radiation environment.

The devices had been irradiated until predetermined total doses were reached. For the purpose of avoiding the effects of recombination in semiconductor after irradiation, all measurements were performed within the time interval between half an hour and two hours after the exposure. Devices in γ radiation field were exposed to total dose of 3 kGy(Si), with dose rate of 5.5 cGy(Si)/s, while the samples in X radiation field absorbed dose of 1 kGy(Si), with dose rate of 11.6 cGy(Si)/s.

More details about experiment, the sources of ionizing radiation and test procedure were provided in references [12],[13].

4. Results

4.1. Serial PNP Transistor Maximum Collector Current

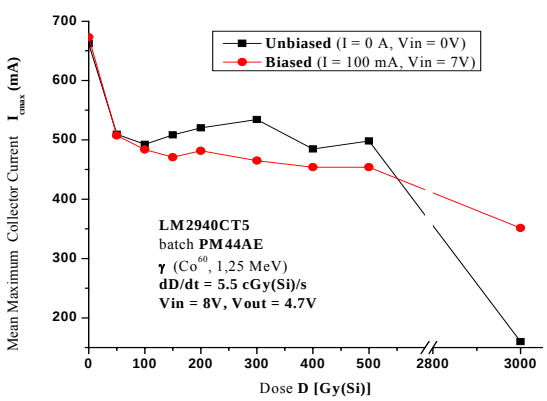

Fig. 8. Change of maximum collector current on serial transistor of voltage regulator LM2940CT5 under influence of γ radiation (batch PM44AE).

Fig. 8 shows the change of maximum collector current mean value for IC's LM2940CT5 after exposure of unbiased and biased samples to γ radiation, while Fig. 9 shows results related to the tests in X radiation field. Data presented on the figures were obtained by tests of circuits from batch PM44AE, made by "National Semiconductor" subcontractor in China. Results of the examination of maximum output current for IC's LM2940CT5 of the same manufacturer, batch JM41AD, made by "National Semiconductor" plant in United Kingdom, for unbiased circuits exposed to γ and X radiation, are shown in Figures 10 and 11. Both lots were packaged in Malacca, Malaysia.

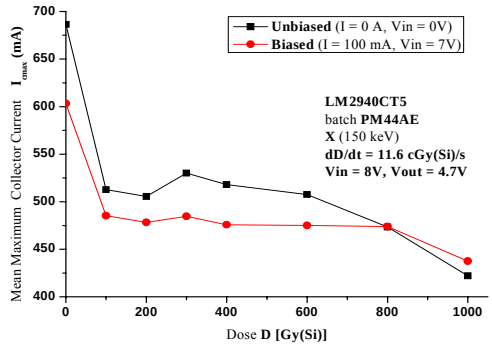

Fig. 9. Change of maximum collector current on serial transistor of voltage regulator LM2940CT5 under influence of X radiation (batch PM44AE).

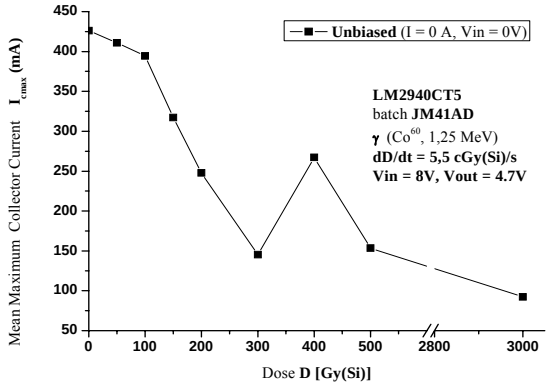

Fig. 10. Change of maximum collector current on serial transistor of voltage regulator LM2940CT5 under influence of γ radiation (batch JM41AD).

The difference in the operation of devices from two different batches is clearly noticable, and it is manifested in the abrupt decrease of maximum output current for voltage regulators from batch JM41AD. Even before irradiation, it could be perceived that devices from batch JM41AD have approximatly 30% less maximum output current then devices from batch PM44AE. After exposure to ionizing radiation, devices from both batches showed the decrease of maximum output current after absorbtion of low ionizing doses (50 - 100 Gy(Si)).

Abrupt decrease of maximum output current shown in Figures 8 and 9 is the consequence of more intense charge trapping in insulator oxide (SiO_2) on the very beggining of irradiation. Low quality insulator oxides (with high dielectric loss factor) have relatively high conductance,

and in the initial phase of exposure to ionizing radiation there begins to happen more intense charge trapping in oxide, causing the increase of surface recombination current and spreading of depletion region in base. After a higher TID is absorbed, oxide becomes saturated in positive charge trapping and recombination rate of trapped positive charge increases, what may lead to slight recovery of serial transistor collector current, regardless the common emitter current gain decrease and increase of base current on medium absorbed ionizing doses. After absorbtion of 100 Gy(Si) dose, maximum output current for devices from batch PM44AE stabilized for TID less then 600 Gy(Si), while devices from batch JM41AD shown additional decrease of maximum current. Difference in the initial values of maximum current, for TID 0 Gy, results from the difference in values of this parameter for the tested samples in the batch, used for calculation of mean value. Unbiased integrated circuits from batch PM44AE had shown slightly higher radiation hardness to the influence of γ and X radiation during the exposure to low and medium TID (less then 600 Gy(Si)), while after exposure to higher ionizing doses biased devices showed much higher radiation hardness.

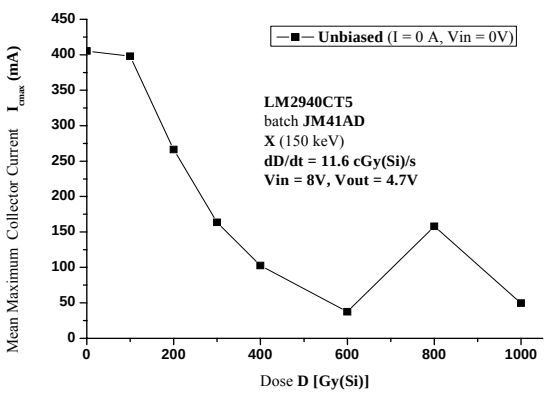

Fig. 11. Change of maximum collector current on serial transistor of voltage regulator LM2940CT5 under influence of X radiation (batch JM41AD).

Presented response of devices from lot PM44AE is unusual for low-dropout regulators, seeing the same circuit topology and similarity of processes used for manufacture of lots PM44AE and JM41AD. However, this is not the first time to notice significant differences between "National Semiconductor" processes in different company's plants all over the world [15], but the observed phenomena are probably among the most expressed evidences of semiconductor devices' characteristics inconsistence for components made by the same manufacturer in different plants.

From Figs. 10 and 11 it can be noticed that the rise of maximum output current for ionizing dose of γ radiation 400 Gy(Si), i.e. TID 800 Gy(Si) for X radiation, is abrupt. This effect is noticable only for unbiased IC's LM2940CT5 from the batch JM41AD, while similar effects were not noticed during the examinations of unbiased samples from the batch PM44AE. Reason for such circuits' behavior originates from tests performed on voltage regulators after the devices absorbed ionizing doses of 300 Gy(Si) (γ radiation) or 600 Gy(Si) (X radiation). In these points were measured characteristics of load regulation. It was noticed that the flow of higher current, especially 500 mA and 700 mA, causes the recovery of output voltage and maximum output current, that is the recovery of common emitter current gain of serial PNP transistor. Supposed reason is the increase of trapped charge recombination in insulator oxide with electrons that flow under the oxide surface. Noticed phenomenon indicates high dielectric loss factor of insulator oxide (SiO_2), i.e. significant variation in insulator oxide quality between two batches of tested integrated circuits. Devices of high radiation hardness are described by high quality of insulator oxide, which manifests in slow degradation of common emitter current gain and slow recovery after irradiation.

4.2. Collector - Emitter Dropout Voltage on Serial PNP Transistor

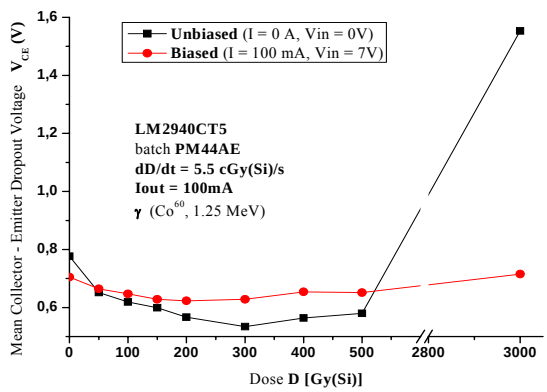

Fig. 12. Change of collector - emitter dropout voltage on serial transistor of voltage regulator LM2940CT5 under influence of γ radiation (batch PM44AE).

Figures 12 and 13 show the change of mean collector - emitter dropout voltage on serial transistor of voltage regulator LM2940CT5 (samples from batch PM44AE) as a function of total ionizing dose of γ and X radiation. Doses below 500 Gy(Si) have not shown significant influence on serial transistor dropout voltage of tested devices. However, for higher ionizing doses (above 500 Gy(Si), for X radiation), it can be noticed that the increase of dropout voltage on serial transistor is considerable. Difference between influence of radiation on dropout voltage of biased and unbiased devices becomes especially significant for devices irradiated in the ^{60}Co field, where it can be noticed that the radiation hardness of unbiased devices is appreciably lower than that of the biased voltage regulators. None of the voltage regulators from batch PM44AE showed drop of output voltage below 4.9V, for load curent 100 mA, regardless of the absorbed TID.

Biased devices in entire ionizing dose range, from 0 Gy to 3 kGy(Si), showed minor variations of serial transistor dropout voltage, while the unbiased circuits manifested significant variations (for lower doses (until 300 Gy(Si), for γ radiation, i.e. 600 Gy(Si), for X radiation) dropout voltage decrease, while the increase of ionizing dose is followed by the increase of dropout voltage).

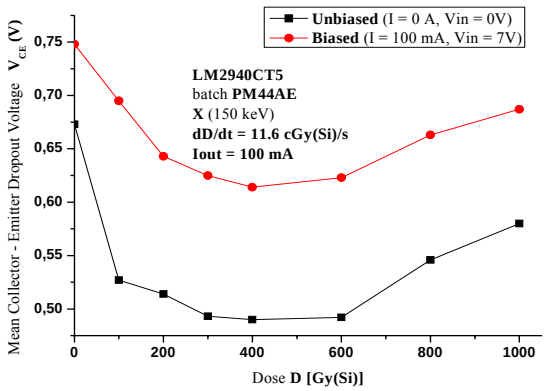

Fig. 13. Change of collector - emitter dropout voltage on serial transistor of voltage regulator LM2940CT5 under influence of X radiation (batch PM44AE).

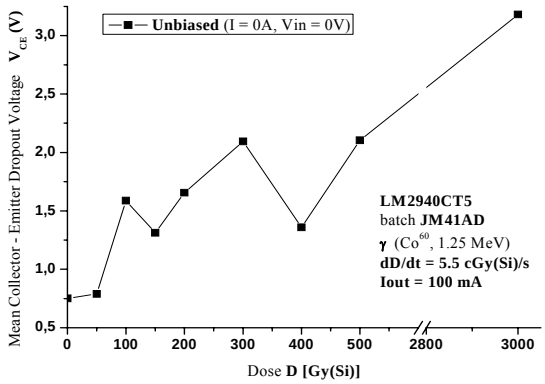

Fig. 14. Change of collector - emitter dropout voltage on serial transistor of voltage regulator LM2940CT5 under influence of γ radiation (batch JM41AD).

Fig. 14 shows the change of mean dropout voltage on serial transistor of circuit LM2940CT5, as a function of absorbed dose of γ radiation, for samples from the batch JM41AD. Significantly higher degradation of serial transistor dropout voltage was perceived than in the case with devices from the batch PM44AE. Also, no voltage regulator from batch PM44AE showed the decrease of output voltage bellow 4.9V, for load current of 100 mA, regardless of the absorbed TID.

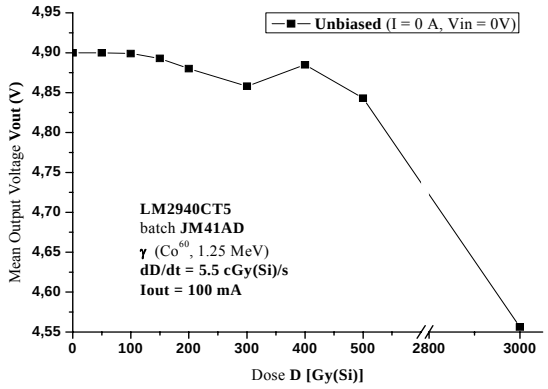

Fig. 15. Change of maximum output voltage of voltage regulator LM2940CT5 under influence of γ radiation (batch JM41AD).

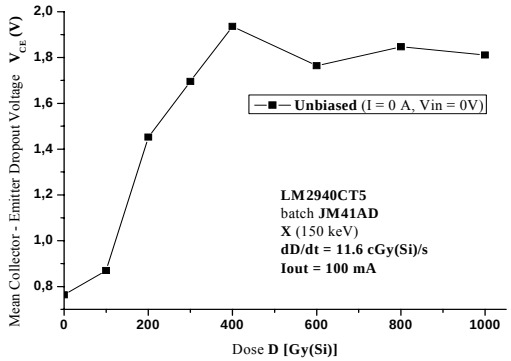

Fig. 16. Change of collector - emitter dropout voltage on serial transistor of voltage regulator LM2940CT5 under influence of X radiation (batch JM41AD).

According to the Early effect, increase in collector - emitter voltage, V_{CE}, induces decrease of base width (for constant base current) and, subsequently, increase of collector current I_C. However, presented results indicate completely oposite response of irradiated serial PNP power transistor. The main reason, especially immediately after the start of irradiation, is very intensive positive charge trapping in the oxide above the base - emitter region, causing the decrease of emitter injection efficiency. After the low total dose is absorbed, increased recombination between trapped positive charge in the oxide and electrons in the base region cause the increase of base current and slight recovery of collector current, only to experience additional current decrease and reduction of common emitter current gain after device's exposure to the high total doses. Seeing the serial power transistor consists of 350 PNP transistors with small perimeter-to-area ratio, it is noticable that significant emitter crowding occured for small total doses. Therefore, decrease of emitter injection efficiency due to high concentration of charge in oxide,

N_{ox}, is the main reason for decrease of I_C simultaneously with increase of V_{CE}.

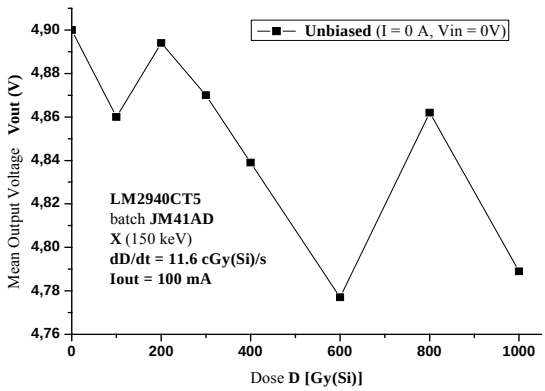

Fig. 17. Change of maximum output voltage of voltage regulator LM2940CT5 under influence of X radiation (batch JM41AD).

For IC's LM2940CT5 from the batch JM41AD, already after the dose absorbtion of 100 Gy(Si) maximum output voltage for current of 100 mA fell below 4.9V, as can be seen in Fig. 15. Output voltage no longer provides the sufficient information about the degradation of serial transistor current gain, necessary to monitor the degradation in change in output voltage (Fig.s 16 and 17 show collector-emitter dropout voltage and output voltage degradation for voltage regulators from batch JM41AD in X radiaton field).

During the measurements, output voltage instability was perceived on devices from batch JM41AD: during the exposure of voltage regulators to higher load current, an increase of output voltage occured. This is the consequence of annealing process. It was noticed that recombination rate increased on higher load currents, and that was the reason why the samples were held in these modes during the measurements as short as possible. On Figs. 14 - 17 particular characteristics recovery can be noticed for devices from batch JM41AD after they absorbed radiation dose 300 Gy(Si) (field ^{60}Co), i.e. 600 Gy(Si) (in X radiation field), similarly to the phenomena from Figures 10 and 11. In this case also, during the recording of load regulation characteristics, increase of recombination rate appeared, which was caused by the flow of high load current through the voltage regulator's serial transistor. Assumed reason for this to happen is again high dielectric loss factor of insulator oxide, i.e. recombination of trapped positive charge with electrons originally from current flow through the serial transistor, in the proximity of oxide surface.

4.3. Load regulation characteristics

In Fig. 18 was shown load regulation characteristic for voltage regulator LM2940CT5 (samples from batch PM44AE) after exposure of unbiased devices to the γ radiation, while in Fig. 19 was shown load regulation characteristic for unbiased devices from batch PM44AE in the field of X radiation photons.

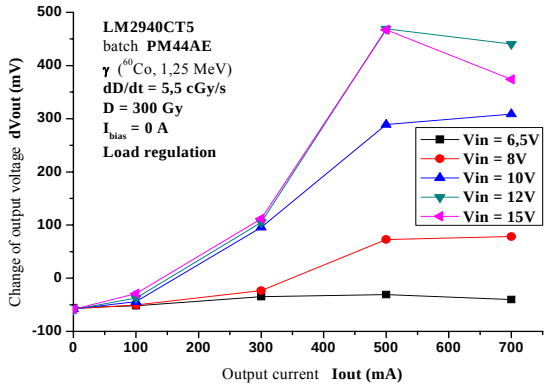

Fig. 18. Load regulation characteristics of unbiased voltage regulator LM2940CT5 after exposure to γ radiation dose of 300 Gy(Si).

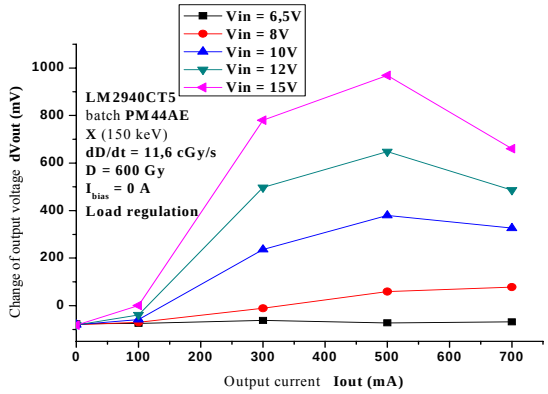

Fig. 19. Load regulation characteristics of unbiased voltage regulator LM2940CT5 after exposure to X radiation dose of 600 Gy(Si).

Voltage regulators mostly kept the regulation ability, but the decrease of output voltage is completely unacceptable for device designed to obtain stabilized voltage on its output. For unirradiated device, change of output voltage specified by the manufacturer is 35 - 50 mV [2], so the changes of 500 mV or 1000 mV for levels of total doses 300 - 600 Gy (Si) indicates severe degradation of pass transistor common emitter current gain. Despite the noticed recovery of collector current and collector - emitter voltage in Figs. 8, 9, 12 and 13, during the experiments were noticed great variations of output voltage, especially during the measurements with high collector currents. Good example is slight recovery of output voltage after the examinations with current 700 mA. This is mainly due to high recombination of trapped positive charge in the oxide, indicating high dielectric loss factor of examined oxide.

For lower input voltages and load currents a negative change of collector voltage (i. e. increase of output voltage) could be perceived. Increase of output voltage for lower currents and abrupt decrease for higher currents indicates particular loss of regulation ability and degradation of other transistors in the voltage regulator beside the serial power transistor, especially error amplifier circuit and negative feedback loop [16].

Although the examinations of collector current and collector - emitter voltage did not show decisive degradation of voltage regulator's characteristics, load regulation characteristics showed that devices from batch PM44AE, also as components from batch JM41AD, experienced complete functional failure after total doses 300 Gy(Si) (in γ radiation field) and 600 Gy(Si) (in X radiation field).

5. Conclusion

Examinations of collector current and collector - emitter voltage of LM2940CT5 voltage regulator's serial transistor, also as voltage regulator load regulation characteristics, showed significant degradation after exposure to moderate levels of total ionizing doses in γ and X radiation environments.

Basic degradation mechanism is decrease of common emitter current gain of serial PNP power transistor, consisting of 350 lateral PNP elementary transistors with round emitters. The main cause for gain degradation of the lateral PNP transistors is increase in surface recombination velocity and is moderated by positive oxide charge. Increase in serial transistor collector - emitter dropout voltage and decrease in collector current are mainly originated by the intensive positive charge trapping in the insulator oxide, causing the reduction of emitter injection efficiency. Increase in surface recombination velocity caused increase of serial transistor base current, having additional contribution to common emitter current gain reduction. Small perimeter-to-area ratio of lateral PNP transistors showed decisive contribution to emitter crowding. Unacceptable variations of insulator oxide quality between two batches also had great impact on LM2940 radiation hardness.

According to the examination results of maximum collector current and collector - emitter dropout voltage on medium total doses (300 - 600 Gy(Si)), devices from batch PM44AE would be characterized as significantly radiation influenced, but functionally correct devices. However, load regulation characteristics lead to complete opposite conclusion, describing tested integrated circuits as radiation soft even for medium TID level. Voltage regulators from batch JM41AD shown functional degradation for all examined parameters. Although good information about voltage regulator radiation hardness may be obtained by the examinations of maximum output current and serial transistor dropout voltage, line and load regulation characteristics remain the basic mean for evaluation of voltage regulator's functional ability and radiation hardness.

Mentioned reasons are arguments to evaluate power integrated circuits made by "National Semiconductor" bipolar process as insufficiently radiation hard, eliminating them as candidates for applications in nuclear reactors and high energy physics systems.

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