The enhanced low dose rate sensitivity of a linear voltage regulator with different biases

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Abstract: A linear voltage regulator was irradiated by ^{60}Co γ at high and low dose rates with two bias conditions to investigate the dose rate effect. The devices exhibit enhanced low dose rate sensitivity (ELDRS) under both biases. Comparing the enhancement factors between zero and working biases, it was found that the ELDRS is more severe under zero bias conditions. This confirms that the ELDRS is related to the low electric field in a bipolar structure. The reasons for the change in the line regulation and the maximum drive current were analyzed by combining the principle of linear voltage regulator with irradiation response of the transistors and error amplifier in the regulator. This may be helpful for designing radiation hardened devices.

Key words: linear voltage regulator; ELDRS; bias dependence
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1. Introduction

Linear voltage regulators are widely used in space systems because of their cost, noise reduction and rapid transient response to load conditions. However, a primary concern in the selection of these devices is their tolerance to the total dose effect, especially the low dose rate ionizing radiation which exists in the space environment. The dose rate of space is different from that in the laboratory, so we have to know whether the dose rate used to evaluate the device is accurate. Moreover, the enhanced low dose rate sensitivity (ELDRS), which results in enhanced degradation of bipolar linear integrated circuits when irradiated at low dose rates, has been reported extensively in Refs. [1–3]. In addition, testing of some linear voltage regulators shows that they exhibit both an ELDRS effect and bias dependency[1−4], but there is little in the literature that discusses the relation between biases and the ELDRS effect. In this article, a bipolar voltage regulator was irradiated at high and low dose rates with different biases to research the influence of the bias on ELDRS.

Figure 1 shows a basic functional block diagram for the linear voltage regulator[5,6]. The integrated circuit includes a band-gap reference, current limiting circuitry, error amplifier and the pass transistor, etc. However, these blocks will degrade during ionizing radiation, and influence the performance of the regulator. If we can find the major blocks which decide the performance of the regulator, it will be helpful in the design of radiation hardened devices. Many references have identified that the degradation of the output voltage is decided by the degradation of the band-gap reference[5,6], and the decrease in the maximum drive current has a relationship with the degradation of the pass transistors[1,3]. However, the current limiting and error amplifier are hardly mentioned. From this research, it appears that they can also change the performance of the regulator during ionizing radiation.

2. Experimental details

Total dose irradiations for the linear regulator were performed at Xinjiang Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. Low- and high-dose-rate irradiations were performed using the weak and strong ^{60}Co gamma rays. High-dose-rate exposure was carried out at 0.5 Gy(Si)/s, which is often used in the laboratory; while the low dose rate was 1.0×10^{-4} Gy(Si)/s, which is the space-like dose rate. After high-dose-rate irradiation, a post-irradiation annealing experiment was performed when the total dose accumulated to 1000 Gy(Si). And the annealing time equaled the irradiation time at low dose rate to confirm whether it's time depended effects of the radiation damage. There were two bias conditions for the samples: zero bias (0 V) and working bias (10 V). Parts in the zero-bias groups，which may be the state

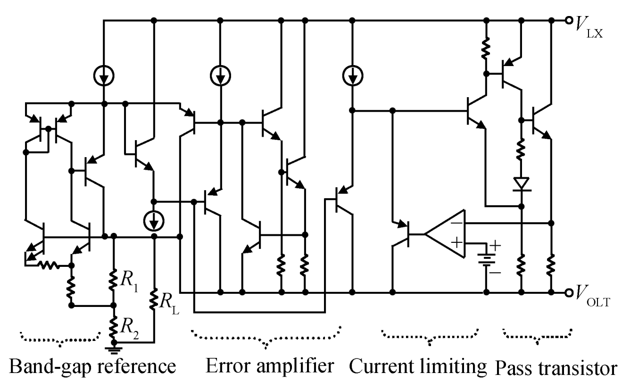

Fig. 1. Basic functional block diagram of the adjustable regulator.

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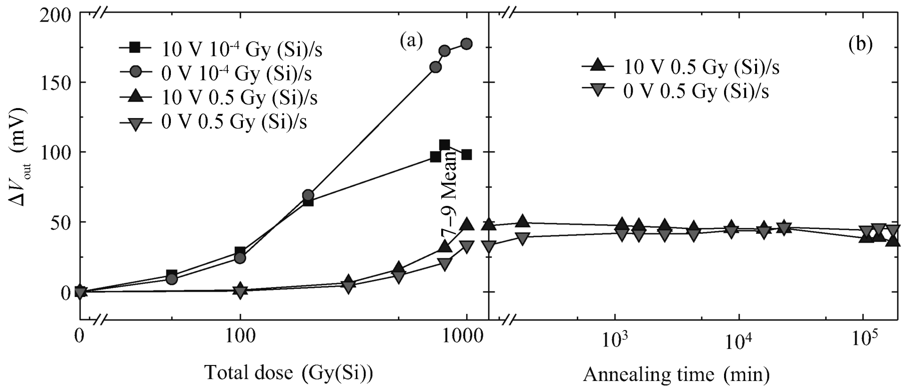

Fig. 2. Change in V_{out} versus (a) total dose and (b) room-temperature annealing time at $V_{out} = 5$ V.

of shutdown or as a backup, had all pins grounded; whereas the working bias, which is the typical application, is shown in Fig. 1. The output voltage was set to 5 V by configuring the proper resistances (R_1, R_2) when the input voltage was 10 V and the load resistance (R_L) was 500 Ω. The bias conditions were held constant during high- and low-dose-rate irradiation and annealing. All irradiations were performed inside a Pb/Al shielding box to minimize dose enhancement. Three parts were irradiated for each group. The mean of the experimental data is given in all figures.

The test device, LM1086, is a bipolar adjustable voltage regulator. Its structure is similar to that in Fig. 1. Electrical parameter tests for the parts were performed using an Amida-3001XP automated test system, which can supply a varied current load. So the pulse testing method was used to avoid increasing the temperature of the chip[6]. Electrical characteristics including conventional line, load regulation and the maximum drive current (I_{max}) were analyzed before and after the radiation exposure, and throughout the annealing procedure. The maximum drive current was measured by pulse testing with increasing load currents step by step. First, a standard voltage (V_{stand} : 5 V pre-irradiation) was measured at a constant input voltage with no load current; then the load current was increased until the output voltage dropped 0.3 V below the standard voltage (V_{stand} – 0.3 V = 4.7 V pre-irradiation), where the regulator was beginning to shutdown[1].

3. Results and discussion

3.1. ELDRS of the regulated voltage

The degradation of the output voltage versus the total dose under the various irradiation conditions is shown in Fig. 2. The damage degree changed with the biases and dose rates. At a high dose rate, more degradation was observed under working bias; while at a low dose rate, more degradation was observed under zero bias. Moreover, no matter what the biases were, the damage at a low dose rate was larger than that at a high dose rate, which is the ELDRS effect.

3.1.1. Enhancement factor and annealing factor

In order to explain the relations between the bias and the ELDRS, we introduced an enhancement factor (EF)[4] and an annealing factor (AF). The enhancement factor is the ratio of the changes in V_{out} at a low dose rate to that at a high dose rate with the same total dose,

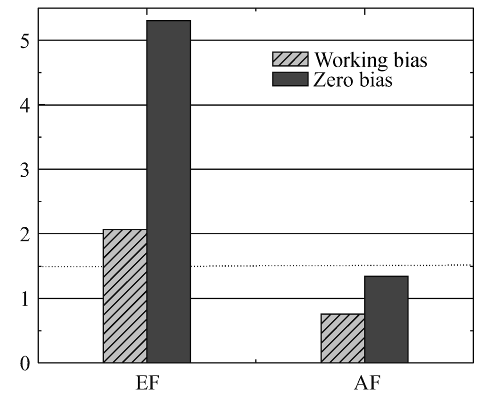

Fig. 3. Enhancement factor and annealing factor under two bias conditions.

$$\mathrm{EF} = \frac{\Delta V_{out} \ @\ \mathrm{LDR}}{\Delta V_{out} \ @\ \mathrm{HDR}} \ @\ \text{same total dose}. \tag{1}$$

While the annealing factor is the ratio of the change in V_{out} after annealing to a certain time to that before annealing,

$$\mathrm{AF} = \frac{\Delta V_{out} \ @\ \text{after anneal}}{\Delta V_{out}} \ @\ \text{before anneal}. \tag{2}$$

3.1.2. Bias and ELDRS effects

Figure 3 gives the enhancement factors and annealing factors of the V_{out} with different biases. The enhancement factors were calculated at 1000 Gy(Si), while the annealing factors were calculated after 1.7×10^5 min annealing at room temperature. According to MIL-STD-883G, if the EF exceeds 1.5 for any of the most sensitive parameters, then the part is considered to be ELDRS susceptible. In Fig. 3, the EFs exceed 2 under both biases; so the linear voltage regulator has an obvious ELDRS effect. And the EF under zero bias is larger than that under working bias, more than twice. This implies that the biases have an important influence on the ELDRS and confirms that the ELDRS is related to the low electric field in the oxide of the bipolar integrated circuit. Comparing the AFs between two biases, the damage was decreasing at working bias during the

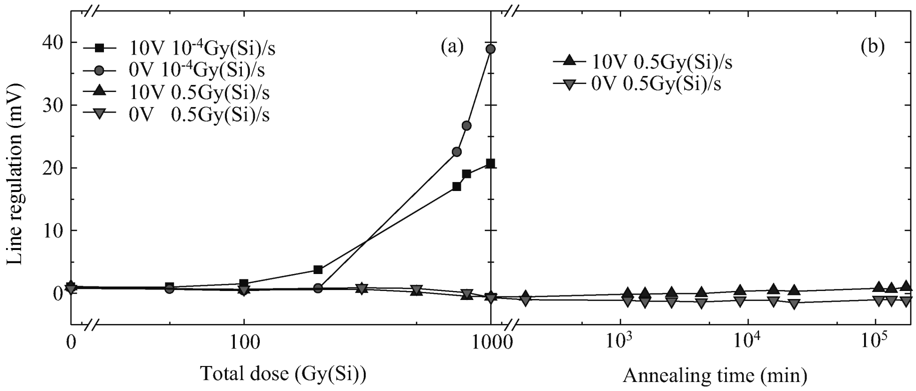

Fig. 4. Line regulation versus (a) total dose and (b) room-temperature annealing time at $V_{\rm out}$ = 5 V.

post-irradiation annealing experiment, while the damage was increasing at zero bias.

The change in $V_{\rm out}$ of the regulator attributes to the degradation of the bipolar transistors which constitute the band-gap reference[5, 6]. And it is generally accepted that the primary causes of the degradation mechanism of bipolar transistors are the interface state and the oxide trapped charge in silicon dioxide[4, 7–10]. The interface state and positive oxide charge can both make the base current increase, and result in the degradation of the integrated circuits. But their performances are different during post-irradiation annealing. Many oxide trapped charges can even anneal at room temperature. In contrast, the interface trapped charge is typically not significantly annealing below 100 ℃[7, 11], and more slow interface states can be generated during the long time annealing at room-temperature. If the AF is less than one (working bias), it is due to the annealing of the oxide trapped charges; if the AF exceeds one, it implies that the generation of interface states is more than the annealing of the oxide trapped charges, which is the situation of zero bias. For the different AFs, it can be concluded that the proportion of interface state is larger under zero bias than that under working bias.

The ELDRS effects can be explained according to the space field[3, 7–10]. For the case of high dose rate, a great number of oxide trapped charges are produced in the SiO_2 layer at the beginning of the irradiation. These charges will generate a strong space field to block the transfer of the radiation-induced holes and H^+. Only a few of them would reach the Si/SiO_2 interface to form a few interface states after a long time. However, the generating rate of electron-hole pairs is slow at a low dose rate, which will result in less oxide trapped charges in the oxide. Thus, the space field will be sufficiently weak; moreover, the long-term radiation will enable the hole and H^+ to have enough time to arrive at the interface, and react with dangling bonds to generate the interface state. Therefore, the interface states are much more at a low dose rate than those at a high dose rate[3, 7–10]. So the ELDRS is formed. Under zero bias, more interface states are generated at a low dose rate for its large proportion; and result in larger EF.

3.2. Reasons for the change in the line regulation

Figure 4 shows the behavior of the line regulation, which has the same performance as the $V_{\rm out}$. The line regulation refers to the changes in the output voltage due to power supply (input) voltage variations. It can be attributed to two error amplifier performance parameters: power supply rejection ratio (PSRR) and common mode rejection ratio (CMRR). In modern integrated circuit regulator amplifiers, the utilization of constant current sources gives such large values of PSRR that this effect on $V_{\rm out}$ can usually be neglected pre-irradiation. However, the PSRR will decrease due to the degradation of the current sources after irradiation[10]. Moreover, considering the CMRR, the $V_{\rm out}$ is influenced by the CMRR through Eq. (4)[12]. Calculating the different output voltage under two input voltage with Eqs. (3) and (4), the relationship between the line regulation and the CMRR can be determined by Eq. (5). The decrement of CMRR[13] during ionizing radiation will lead to the increment of the line regulation, just as in Fig. 4,

$$V_{\rm cm} = V_{\rm Ref} - \frac{V_{\rm in}}{2}, \tag{3}$$

$$V_{\rm out} = \left(V_{\rm Ref} - \frac{V_{\rm cm}}{\rm CMRR}\right)\left(1 + \frac{R_2}{R_1}\right), \tag{4}$$

$$\Delta V_{\rm out} = \frac{\Delta V_{\rm in}}{\rm CMRR}\left(1 + \frac{R_2}{R_1}\right). \tag{5}$$

$V_{\rm cm}$ refers to the common mode voltage, $\Delta V_{\rm in}$ refers to the difference between two input voltages, while $\Delta V_{\rm out}$ refers to the difference between output voltages at two input voltages.

3.3. Change in the maximum drive current

Figure 5 gives the performance of the maximum drive current under various irradiation conditions. It increases at high dose low. But at low dose low, it decreases under zero bias, while decreasing then increasing to more than the original value under working bias. It is well known that the maximum drive current is a function of the gain of the pass transistors[3]. But the current limiting circuit, which will cut off the output of the regulator when the load current or the power exceeds the setting value, has an important influence on the maximum drive current. After irradiation, the performance of the current limiter and pass transistors degrades. From Fig. 1, it appears that when the drive current is less than the setting value, the amplifier of the current limiter gives a high value, and the PNP transistor is cut off; otherwise, it will be active, and let the $V_{\rm out}$ drop to a very low value (cut off the output). We conclude that the increase in the bias voltage/current of the amplifier or the degradation of the transistor gain, used in the current limiter, will

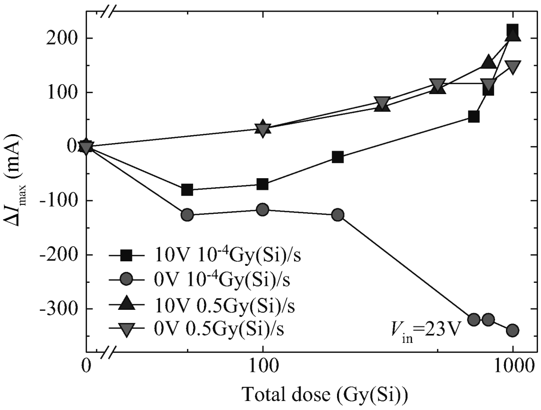

Fig. 5. Change in I_{max} versus total dose under various irradiation conditions.

degrade the performance of the current limiter. It needs more current or power to cut off the regulator due to the degradation of the current limiter, while the regulator can drive less load current due to the degradation of the pass transistors. When the degradation of the current limiter is greater than that of the pass transistors, the maximum drive current will increase; otherwise, it will decrease. If it increases, the regulator will source excessive load current at some worse case and destroy the pass transistors; if it decreases, the regulator cannot drive the setting load current. Thus, the maximum drive current should be considered during radiation hardness testing.

4. Conclusions

The output voltage, the maximum drive current and the line regulation of the regulator are sensitive to total doses and dose rates. All of the key electrical parameters should be measured during hardness assurance testing. The ELDRS effect has a relation to the biases. More obvious ELDRS is achieved at zero bias. And the worst-case space system application is in unbiased spares.

Though the reference decides the change in the output voltage of the regulator; the pass transistor, the error amplifier and even the current limiting circuit will all degrade after ionizing irradiation, and lead to the degradation of the regulator parameters. One has to pay attention to them when designing radiation hardened devices.

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