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An Accelerated Simulation Method for ELDRS of Bipolar Operational Amplifiers Using a Dose-Rate Switching Experiment

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Abstract: Through different dose-rate switching evaluation methods, the radiation-response rules of operational amplifiers are studied when the irradiation dose rate is switched from high to low under different radiation temperatures and total doses. The experimental results indicate that the response characteristics could be affected by the switching total doses, irradiation temperatures, and dose rates individually or together. Accelerated evaluation on the ELDRS can be realized by adopting a proper dose-rate switching method. Meanwhile, the irradiation time can also be reduced. Finally, the mechanisms of the difference between various radiation responses are analyzed.

Key words: bipolar OP-amps; ^{60}Co γ radiation; switching dose rates; accelerated evaluation
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1 Introduction

Since 1990s, numerous research papers have been published abroad on the enhanced low-dose-rate sensitivity of bipolar devices. It has been found that the total-dose damage threshold for bipolar devices is much lower under a real low-dose-rate radiation environment that has a dose-rate-range between 10^{-4} and 10^{-2}rad(Si)/s than under high dose rates from 50 to 300rad(Si)/s, which is often used in labs. The existence of ELDRS may make the radiation hardening levels of electronic devices, which are obtained based on laboratory evaluation methods, much different from those obtained in a real space radiation environment. So, this may pose a threat to the reliability of the electronic systems of satellites or space stations. However, it is waste of time and uneconomical if we evaluate the hardness level of the devices with low-dose-rate irradiation. Therefore, finding an efficient, reliable, and applicable method to evaluate ELDRS of bipolar devices in laboratories is significant.

Recently, the ELDRS effect and its mechanism in bipolar devices have been widely researched abroad and several theoretical models been proposed. Thus far, there is no unanimous conclusion, because the ELDRS effect is highly dependant on the structures and technical procedures of the devices. The investigation of accelerated evaluation is mostly focused on elevated temperature irradiation at high dose rates, though there are some reports on dose-rate switching irradiation[1~7]. The revised American military standard (the standard for short) —MIL-STD-883G was issued recently, but its content about the evaluation method of ELDRS is obscure. The applied dose rate and at which total dose level to switch are not included in the standard. Domestically, only recently have investigations of ELDRS started, and now the study is mainly still focused on low-dose-rate irradiation, while reports on accelerated evaluation of ELDRS are quite rare.

As for the current study situation of ELDRS and disadvantages of the accelerated evaluation methods proposed in the standard, a series of dose-rate irradiation switching methods are explored in this paper. We find that accelerated evaluation of ELDRS can be achieved by adopting proper switching total dose and dose rate. Meanwhile, the irradiation time can be less than that needed by the standard. The underlying mechanisms of these methods are analyzed in this paper.

2 Experimental samples and methods

The samples are bipolar operational amplifiers, LM108, with an obvious ELDRS effect and which are typically used on satellites. The radiation sources are our institute's strong and weak ^{60}Co gamma rays, with 2.59×10^{15} and 3.7×10^{13}Bq, respectively. The biasing conditions were held constant during the experiments, that is, the positive terminal is grounded, while the negative terminal is connected to the output, and

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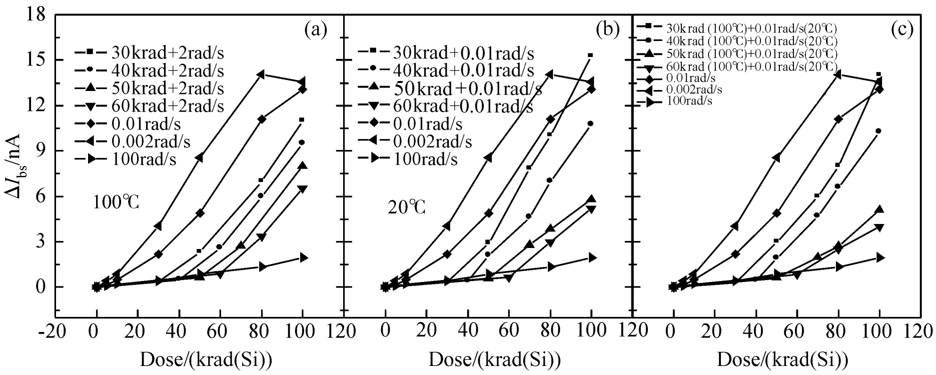

Fig.1　I_{bs} of LM108 versus the total dose at various dose-rate switching methods　(a) 1st method; (b) 2nd method; (c) 3rd method

the supplies are ±10V.

Thermal luminescent dosimeters were equipped on each radiation board during room-temperature irradiation to measure and verify the real dose rate and the total dose, so as to ensure that the experimental data are precise. The samples were placed in Pb/Al shielding boxes made according to the standard, so as to avoid the low-energy scattering and prevent the dose-enhancement effect.

The elevated temperature irradiation is performed in a special box with constant temperature. There is a very sensitive and radiation hardened thermal resistance in the special box in order to ensure that the temperature shift in the box is within ±2℃.

The parameters of operational amplifiers were performed on a Tektronix 577-178 curve tracer. The parameters to be measured, before and after irradiation, are as follows: input offset voltage (V_{io}), input biased current (I_{bs}), common mode rejection ratio (CMRR), AVOL, and SVRR. The test for all these parameters was finished within 20min after an irradiation.

For the evaluated methods such as high dose rate irradiation at elevated temperature (1 ~ 5rad/s, 100℃) and low dose rate (0.01rad/s) irradiation at room temperature proposed in the standard, a group of dose-rate-switching experiments were conducted to study the influence of various methods of switching dose rates on radiation responses. The experimental methods are as follows:

The devices are irradiated at a high dose rate of 50rad(Si)/s, the base-line dose rate in the standard. Then, the dose rate is switched to 2rad(Si)/s at total doses of 30, 40, 50, 60krad(Si), respectively. All the devices are irradiated to 1×10^5 rad(Si). The temperature is 100℃ during each procedure. This is the first method, above. The second method is similar to the first, only the low dose rate is altered to 0.01rad (Si)/s and the temperature is 20℃ for each procedure. The third one is also similar to the first, the only difference is that the low-dose-rate (0.01rad(Si)/s) irradiation is performed at room temperature (20℃).

3　Results and discussion

The radiation responses of the operational amplifier, LM108, were observed under three different conditions by switching dose-rate methods. LM108 is quite sensitive to ionized radiation and most of the tested parameters are degraded to certain extents. The change on the biased current, I_{bs}, is most obvious.

The I_{bs} of LM108 versus total dose at three different radiation methods are shown in Fig. 1. For comparison, the irradiation results at low dose rates, 0.002, 0.01, and 100rad(Si)/s, are also given in the figure.

Figures 1 (a), (b), and (c) indicate that I_{bs} decreases gradually as the switching total doses increases for the three irradiated methods. The shifts of I_{bs} using any one of these irradiation methods are all the same as those at 100rad(Si)/s when it is irradiated with 50rad(Si)/s. Once the dose rate is switched to a low dose rate, the slopes of the curves will change and are basically the same as those irradiated at a low dose rate when the switching dose is lower than 40krad (Si). This phenomenon is most obvious in Fig. 1(a) with the elevated temperature radiation method. When adopting this method, no matter what the total switching dose is, all the subsequent low-dose-rate irradiations result in the same slopes as an irradiation is conducted entirely at low dose rate, only the levels of damage are step-by-step smaller. Thus, if we want to evaluate radiation damage with the shortest time qualitatively, the first method is a worthwhile approach. If the corresponding factors can be found, the irradiated damage then can be evaluated via multiple factors either qualitatively or quantitatively.

To visually compare the disadvantages and ad-

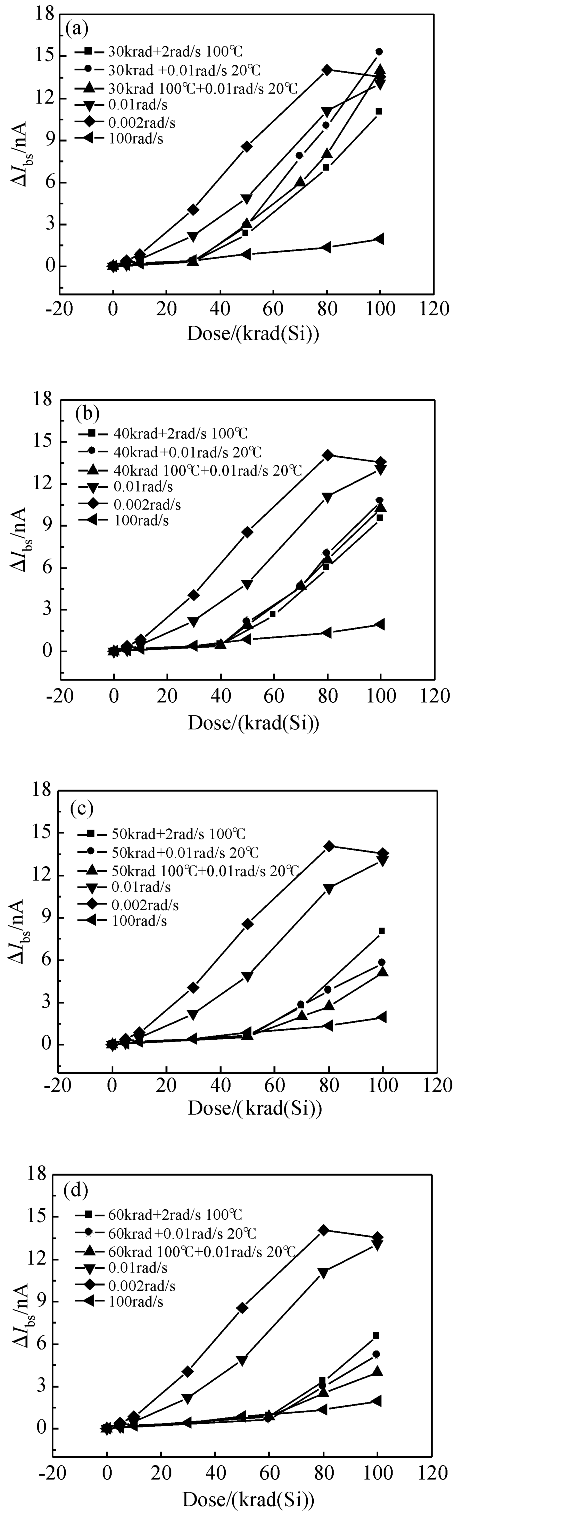

Fig.2 I_{bs} of LM108 versus the total dose at the same switching dose and different irradiation methods

vantages of the three methods, the responses of the bias current I_{bs} of LM108 with different radiation methods at the same total dose are illustrated in Fig. 2. Comparison shows that the radiation responses are little different at various total doses. The response rule differs before and after 40krad(Si). The damage of the first method is always bigger than the other two radiation methods after this total dose, while it is

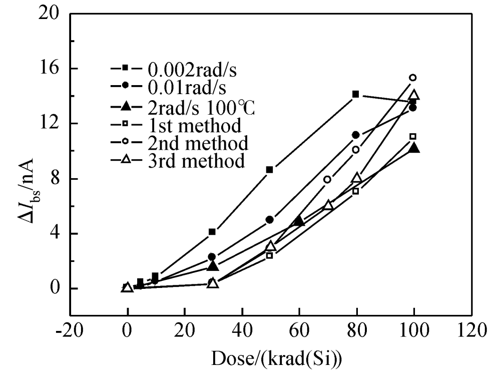

Fig.3 I_{bs} of LM108 versus different radiation methods

reverse before it. By comparing the irradiated damages with the room-temperature irradiation (the second method) and room-temperature irradiation after elevated temperature irradiation (the third method), it can be obtained that the radiation damage of the second method is larger than that of the third.

Figure 2 also demonstrates that the result obtained by switching to low dose rate at 30krad(Si) is closer to that of low dose rate irradiation for the four total doses. Comparing the second and the third method, the result of the third method is closer to the real radiation result, while that of the second method is more conservative and its damage margin is greater than the other two methods. In order to compare the most efficient radiation method presented above with the standard method, we plotted the results together, as shown in Fig. 3. The results include two parts. One part is the results obtained by switching to room- and high-temperature, low dose rate radiation at 30krad (Si) using the first, second and third radiation method, respectively. The other part is the value obtained by the real, very low dose rate irradiation and constant dose rate irradiation at constant temperature, 2rad(Si)/s and 100℃, in the standard.

Figure 3 shows that it does not no matter whether it is room-temperature irradiation or a dose-rate switching irradiation at elevated temperature, the radiation damages at high dose rate radiation of both cases are always smaller than that at constant low dose rate irradiation. However, in the procedure of a low dose rate irradiation following it, the irradiation damages would be gradually bigger than those of a corresponding constant dose rate irradiation. The different damage mechanisms of high and low dose rate irradiations are responsible for this phenomenon.

A great number of oxide trapped charges are produced in the base oxide layer for the high dose rate irradiation case[2]. These charges form a space field in the oxide layer to block the radiation-induced holes and hydrogen ions to reach the Si/SiO_2 interface. After a long time, only a few radiation-induced holes and hydrogen ions reach the Si/SiO_2 interface to form the interface state. But under the low dose rate condition, the radiation-induced oxide charges are fewer, and the space field formed by these charges is weaker. Thus, the radiation-induced holes and hydrogen ions have enough time to transport to the Si/SiO_2 interface and react with the dangling bonds there to generate interface trapped charges. These interface trapped charges can become the recombination centers in the base surface. Consequently, they increase the excessive base current, decrease the current gain of transistors, and enhance the radiation damage at low dose rate.

According to the mechanisms above, the blocking space field created by radiation-induced oxide charges at high dose rate correspondingly results in less damage irradiated at 50rad(Si)/s, as shown in Fig. 3. As total dose increases, the situation may be different. When the dose rate switches from high to low, it will make the space field gradually weaker. At the same time, due to more radiation time, radiation-induced active species such as hydrogen ions and holes, etc., get adequate time to transport to the Si/SiO_2 interface, react there with the dangling bonds to create interface trapped charges, and result in stronger current-gain degradation. Moreover, Reference [12] shows that a mass of species produced at high dose rate irradiation would be trapped near the interface. When the dose rate lowers, these species can migrate to the interface, participate in the reactions of the interface state, and exacerbate the damages. They are also the reason that dose rate switching methods enhance rather than decrease the radiation damages.

When carefully looking at Fig. 3, we also find that in elevated temperature irradiation, the damages caused by constant or varying dose rate radiations are approximately the same. They are close to but can not reach the damage levels derived from a low-dose-rate irradiation, as illustrated in figures for the results of 2 rad(Si)/s 100℃ in the standard and the first method. However, the damages with room-temperature 0.01 rad(Si)/s irradiation after irradiated with a high dose rate at room or elevated temperatures, are bigger than those of the irradiations with a low dose rate. There are two factors responsible for this phenomenon. On the one hand, the probability of interface-state production increases, due to the longer radiation time at 0.01rad(Si)/s than that at 2rad(Si)/s. On the other hand, the quick accumulation of the interface state occurs at high total dose. These two factors result in an increase of the excess base current. Thus, the degradation of transistor gain is accelerated.

Moreover, Figure 3 indicates that although the experimental method is transferred down to a low dose rate of 0.01rad(Si)/s irradiation from 50rad(Si)/s, the damages at room-temperature are much larger than those of room temperature irradiations after an elevated temperature irradiation. The reason is closely dependent on the radiation characteristic of the input stage of LM108 operational amplifiers and npn transistors. Reference [13] indicates that ionizing damages of npn transistors are not only dependent on the interface state, but also on oxide trapped charges. The annealing temperature of oxide trapped charges is different from that of the interface state. The annealing temperature of oxide trapped charges is lower, and could easily anneal even at room temperature. Meanwhile, the required temperature for the interface-state to anneal is higher. Generally, elevated temperature radiation even as high as 100℃ anneals many oxide trapped charges, but this will not affect the formation of the interface trapped charges[14~16]. For the LM108 operational amplifiers with npn transistor as its input stage, radiation at elevated temperature can reduce the influence of the space field; but at the same time, the radiation damages decrease because of the remarkable annealing of oxide trapped charges. Therefore, damages at room temperature are larger than at high temperature for the same total dose.

Furthermore, Figure 1 and Figure 2 suggest that low dose rate switching at different doses after high dose rate irradiation directly affect the radiation characteristics. This is because both the creation and annealing of oxide-trapped-charges and interface-state are dependent on the radiation time and total dose. If the radiation time is too long, the oxide trapped charges will anneal. If it is too short, there is not enough time for the interface state to form. These two factors always interact and impact each other, so it is critical to select an appropriate total dose at high dose rate irradiation if a dose rate switching method is selected.

Figure 3 also shows that the damages at very low dose rate irradiation, such as at 0.002rad(Si)/s, will saturate. This is caused by the consequent annealing of oxide trapped charges and interface state, during such a long time radiation (about 579 days). So, the damages decrease as the radiation time increases. Through comparison, radiation time for a dose rate of 0.01rad(Si)/s is more proper for testing ELDRS. But the time needed at this dose rate is also too long and could be about 116 days. This time length is still too long to make an evaluation for most devices. However, when using dose rate switching methods, the radiation time can be obviously reduced and ELDRS can also be simulated at the same time. Taking the second method in Fig. 3 as an example, the radiation time is 81 days, 35 days shorter than the time needed by irradiation at 0.01rad(Si)/s. With approximately the same result, the time needed by the first method is about 9 hours, 5 hours shorter than that needed for 2rad(Si)/s 100℃ irradiation. Consequently, the first method is the most efficient and economical of these methods for evaluating the irradiation damage of devices.

4 Conclusions

The following conclusions can be obtained by this research:

(1) Irradiation characteristics are affected by radiation temperature, switching total dose, and dose rate, through the investigation of three different dose-rate switching evaluation methods. The best effect can be reached when the switching dose is 30krad(Si) in the dose-rate switching methods studied above. Switched at this total dose, the first method is the simplest and quickest evaluation method. The result of the second method is very close to the result at low dose rates. The radiation damage margin given by the third method is greatest and this method is the most conservative evaluation. These three evaluation methods all can take less radiation time than the constant dose rate irradiation in the standard do, while at the same time they can simulate ELDRS effects as expected.

(2) It is critical to select a proper irradiation temperature, switching dose, and dose rate in adopting the dose rate switching approach. This can determine whether it properly simulates ELDRS of devices because the damaging mechanisms are closely related to the radiation-induced oxide charge and interface state. The creation and annealing of these trapped charges directly correlate with the radiation time, radiation temperature, and total dose. These factors interact and impact each other. If these factors are properly selected, then a satisfying result can be expected.

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双极运算放大器 ELDRS 效应的变剂量率加速模拟方法初探

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摘要：采用不同的变剂量率加速评估方法，研究了在不同辐照温度、不同辐照总剂量条件下，运算放大器电路随高剂量率转换到低剂量率的辐射变化规律．结果表明，辐照时的转换总剂量、辐照温度及辐照剂量率均会对器件的响应特性产生影响，采用合适的变剂量率辐照方法可以达到既缩短辐照时间，又能加速评估器件 ELDRS 效应的目的．另外，对产生各种响应差异的机理进行了分析．

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