Effect of ionizing radiation on dual 8-bit analog-to-digital converters (AD9058) with various dose rates and bias conditions*

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The radiation effects on several properties (reference voltage, digital output logic voltage, and supply current) of dual 8-bit analog-to-digital (A/D) converters (AD9058) under various biased conditions are investigated in this paper. Gamma ray and 10-MeV proton irradiation are selected for a detailed evaluation and comparison. Based on the measurement results induced by the gamma ray with various dose rates, the devices exhibit enhanced low dose rate sensitivity (ELDRS) under zero and working bias conditions. Meanwhile, it is obvious that the ELDRS is more severe under the working bias condition than under the zero bias condition. The degradation of AD9058 does not display obvious ELDRS during 10-MeV proton irradiation with the selected flux.

Keywords: analog-to-digital converters, enhanced low dose rate sensitivities (ELDRS), gamma ray and proton irradiation, lower/high-dose rate

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1. Introduction

Analog and mixed signal semiconductor devices have important applications in spacecraft. Charged particles, like protons and electrons, being abundant in space, could be incident on the semiconductor devices, producing radiation damage.[1–6] Therefore, in space applications, radiation damage to analog and mixed signal semiconductor devices is a major concern. Over the years, the radiation damage to analog-to-digital (A/D) converters induced by gamma rays has been researched and reported.[7–10] During these studies, the enhanced low dose rate sensitivity (ELDRS), which has been studied extensively on bipolar linear integrated circuits,[11–15] has been shown to exist in A/D converters.[7,10,16] There are many electrical parameters for ADCs, such as integral nonlinearity, reference voltage, supply current, and so on. However, few references are able to show what electrical parameters are sensitive to ELDRS.

In space applications, A/D converters are employed in the low dose rate environment. The electrical parameters of A/D converters reveal clear differences under various bias conditions in the low dose rate environment. Unfortunately, few references could be used to obtain this information. In Ref. [16], the differences, induced by various biases, have been researched for the bipolar analog-digital mixed circuit (AD571), which shows that devices under the zero bias condition will degrade more severely than those under a working bias condition of gamma ray irradiation with low dose rate. This conclusion is useful for AD571 employed in spacecraft, because different bias conditions should be considered for space applications. However, the universality of this conclusion needs to be further proved.

Moreover, up to now, there has been no reference to the radiation damage to A/D converters induced by protons. The study of proton radiation induced effects on A/D converters, in general, is important for both the basic research and the practical applications from a space point of view. On the one hand, it is helpful to understand the total ionizing dose (TID) effects, especially ELDRS; on the other hand, it is useful to assess A/D converters operating in a space radiation environment, where energetic protons could induce radiation damage to the devices.

The objective of this investigation is to examine the radiation effects on A/D converters, induced by 10-MeV proton and gamma ray irradiation at various dose rates. The reference voltage, digital output logic voltage, and supply current of A/D converters (AD9058) are measured under gamma ray irradiation with low/high dose rate, to show which electrical parameters are sensitive to ELDRS. The same electrical parameters are measured under 10-MeV proton irradiation, to reveal proton radiation damage to ADCs. In order to obtain a detailed evaluation of the bias condition, the A/D converters are under working and zero bias conditions during the gamma ray and proton irradiation. The research on characteristics and mechanisms of ELDRS in ADCs has very important significance for the reliability of electronic systems in spacecraft.

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2. Experiment

The A/D converter used in this investigation was the AD9058. The AD9058 combines two independent, high performance, 8-bit analog-to-digital converters (ADCs) in a single monolithic IC. Combined with an optional on-board voltage reference, the AD9058 provides a cost-effective alternative for systems requiring two or more ADCs.[17]

Several testing techniques, including those for measuring the static and dynamic properties of the A/D converters, have been developed for evaluating the radiation effect on the A/D converters.[18–21] The method and complexity of testing were dependent on the parameters to be measured.[7] In Ref. [22] based on measurement results obtained from various testing modes, it was reported that the radiation failure mechanism is independent of the testing mode. That is to say, static parameter measurements are sufficient to evaluate the performances of A/D converters under gamma ray and proton radiation. Therefore, the reference voltage, digital outputs logic voltage and supply current of the A/D converter (AD9058) need to be selected to reveal the radiation damage under gamma ray and proton irradiation. These parameters were obtained by the test setup and are shown in Fig. 1. The test unit in Fig. 1 includes a socket board, logic level converters, bus drivers, current/voltage measurement system, and so on. The irradiation and measurements, before and after irradiation, were made at room temperature, and all of the samples were decapped.

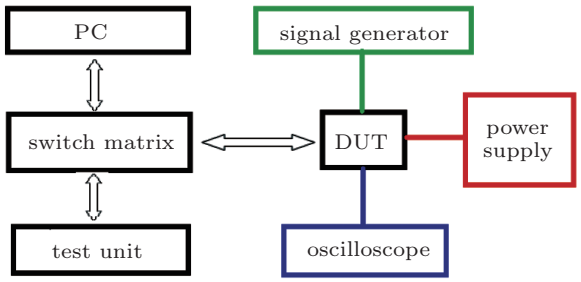


Fig. 1. (color online) Test setup for the ADC structure.

The 10-MeV proton irradiation tests were performed using the EN Tandem Accelerator at the State Key Laboratory of Nuclear Physics and Technology, Peking University, China. The irradiations were performed in the vacuum chamber. The chamber is equipped with a specially designed Faraday cup, which is used to measure beam current. The beam area was defined and held constantly. To ensure the test accuracy, beam uniformity was monitored during irradiation. Based on these measurements, a flux of incident protons, 2.01×10^9 p$\cdot$cm$^{-2}\cdot$s^{-1}, was obtained, of which the uncertainty was less than 10 percent. Then, the total ionizing dose (TID) rate D' produced by monoenergetic charged particle irradiation can be calculated by using the following formula:

$$D^{'}(t) = D_i(t) \times \varphi, \tag{1}$$

where $D'(t)$ is the dose rate as a function of the chip material depth of the device, the unit is rad/s; t is the depth of device chip, the unit is μm; φ is the flux of the incident particles, the unit is cm$^{-2}\cdot$s^{-1} for protons; $D_i(t)$ is the ionizing dose per fluence as a function of depth in chip material of device and could be calculated by using Geant4, the unit is rad$\cdot$cm^2. Based on the results calculated by Geant4, the average $D_i(t)$ is 5.54×10^{-7} rad$\cdot$cm^2 within 100 μm of the ADCs' chip. In this range, the energy loss of 10-MeV protons could be kept stable. Therefore, based on Eq. (1), the dose rate for 10-MeV protons is 1.11×10^3 rad/s in the AD9058.

The gamma ray irradiation tests were performed at Peking University, China. Two dose rates, 0.07 rad/s and 3.35 rad/s, were chosen for the irradiation measurement, of which the uncertainty is less than 5 percent. To avoid low-energy scattering and the dose-enhancement effect, all of the samples were shielded in Pb/Al boxes, as mentioned in ESCC Basic Specification No. 22900 and MIL-STD-883 TM1019.

All of the samples were biased under the working condition (nominal operating configuration) and zero condition during the 10-MeV proton and gamma ray irradiation. Under the working condition, the AD9058 device was biased into the nominal operating configuration, with a +/−5 V power supply and at conversion rate of 40MSPS during irradiation. The internal 2 V voltage reference will be used in the two ADCs. An input voltage of 1.33 V will be applied to both of the $A_{\rm IN}$ (analog input voltage) for an expected value on the output ADC of "10101010". In the zero bias condition, all of the pins were grounded.

3. Results and discussion

3.1. Degradation induced by gamma rays

The reference voltage, digital outputs logic "0" voltage and supply current of ADCs are measured for all of the samples using the same test setup before and after irradiation. From these results, the changes in reference voltage ($\Delta V_{\rm ref}$), digital outputs logic "0" voltage ($\Delta V_{\rm ol}$), and supply current ($\Delta I_{\rm S}$) can be given. The $\Delta V_{\rm ref}$, $\Delta V_{\rm ol}$, and $\Delta I_{\rm S}$ are defined as the reference voltage, digital outputs logic "0" voltage, and supply current after irradiation subtracting their corresponding pristine values, respectively.

There are three samples during the irradiation and measurement, named "1", "2", and "3", respectively. Each sample (AD9058) includes two ADCs, named "A" and "B", respectively. Samples "1" and "2" were biased under the working condition, while sample "3" was biased under the zero condition during irradiation. In addition, the dose rates were 0.07 rad/s and 3.35 rad/s before and after the total ionizing dose at 1.0×10^4 rad, respectively, for samples "1" and "3". For sample "2", the dose rates were 0.07 rad/s and 3.35 rad/s

before and after the total ionizing dose at 7×10^4 rad, respectively. Therefore, samples "1" and "2", with the same bias condition, are under different dose rates, which can show clearly whether the ELDRS exists. Meanwhile, samples "1" and "3", with the same dose rate, are under different bias conditions, which can reveal the influence of the bias condition during irradiation.

Figure 2 shows the changes in reference voltage($V_{\rm ref}$) of the AD9058 as a function of irradiation dose, induced by gamma ray with various dose rates. Based on the results in Fig. 2, it is obvious that the reference voltage of the ADC increases with irradiation dose increasing. Moreover, the reference voltage under the working bias condition degrades more severely than under the zero bias condition during low dose rate gamma ray irradiation at a given total dose. However, during high dose rate gamma ray irradiation, compared with the working bias condition, the zero bias condition can induce more severe degradation of the reference voltage at a given total dose. Therefore, the working bias condition causes more severe damage to the reference voltage during low dose rate irradiation, while the zero bias condition induces more severe degradation of the reference voltage during high dose rate irradiation at a given total dose. In addition, the change in reference voltage of sample "1" is higher than that of sample "2" from 7×10^4 rad to 1.0×10^5 rad, showing that the dose rate has influence on the degradation of reference voltage. The slope of curve of the change in reference voltage of sample "1" is 0.019, and that of sample "2" is 0.005 from 7×10^4 rad to 1.0×10^5 rad.

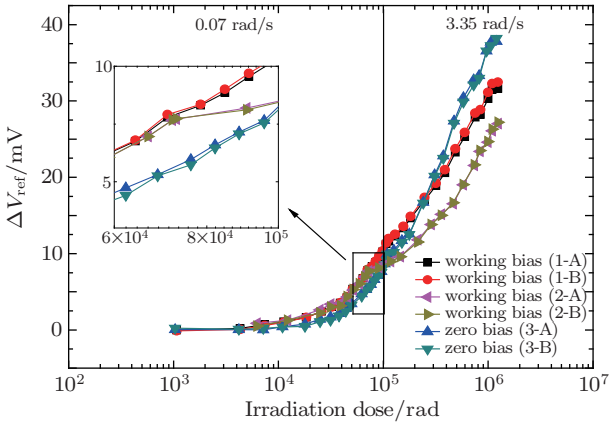


Fig. 2. (color online) Changes in reference voltage of the ADCs ($\Delta V_{\rm ref}$) as a function of irradiation dose, induced by the gamma ray with various dose rates.

Figure 3 shows the changes in supply current $(-I_{\rm S})$, with supply voltage at -5 V, of the AD9058 as a function of irradiation dose, induced by gamma ray with various dose rates. Based on the results in Fig. 3, it is obvious that the supply current of the AD9058 decreases with irradiation dose increasing. Moreover, the supply current under the working bias condition is degraded more severely than under the zero bias condition during low and high dose rate gamma ray irradiation. In addition, the change in supply current of sample "1" is much higher than that of sample "2" from 7.0×10^4 rad to 1.0×10^5 rad, showing that the dose rate has influence on the degradation of supply current. The slope of curve of the change in supply current of sample "1" is -1.337, and that of sample "2" is -0.007 from 7.0×10^4 rad to 1.0×10^5 rad.

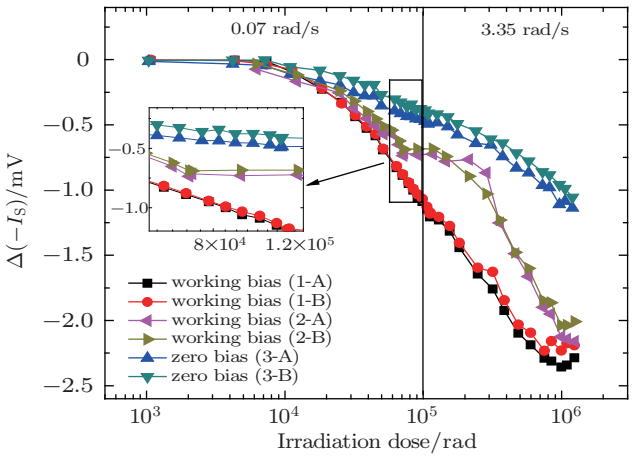


Fig. 3. (color online) Changes in supply current of the ADCs ($\Delta(-I_{\rm S})$) as a function of irradiation dose, induced by gamma ray irradiation at various dose rates.

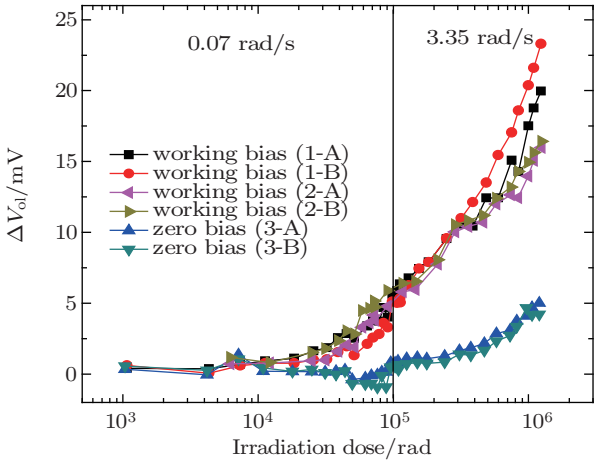


Fig. 4. (color online) Changes in output logic voltage of the ADCs ($\Delta V_{\rm ol}$) as a function of irradiation dose, induced by gamma ray irradiation at various dose rates.

Figure 4 shows the changes in output logic "0" voltage ($V_{\rm OL}$) of the AD9058 as a function of irradiation dose, induced by gamma ray irradiation at various dose rates. Based on the results in Fig. 4, it is obvious that the output logic voltage of the AD9058 increases with irradiation dose increasing. Moreover, the output logic voltage under the working bias condition is degraded more severely than under zero bias condition during the gamma ray irradiation. However, no obvious ELDRS is found during the gamma ray irradiation.

3.2. Degradation induced by proton irradiation

Three samples are investigated during the irradiation and measurement, named "4", "5", and "6". Each sample (AD9058) includes two ADCs, denoted as "A" and "B",

respectively. Samples "4" and "5" were biased under the working condition, while sample "6" was biased under the zero condition during irradiation. The dose rate was 1.11×10^3 rad/s.

Figure 5 shows the changes in reference voltage ($V_{\rm ref}$) of the AD9058 as a function of irradiation dose, induced by proton irradiation with a 1.11×10^3 rad/s dose rate. Based on the results in Fig. 5, it is obvious that the reference voltage of the ADC increases with irradiation dose increasing. Moreover, the reference voltage under the zero bias condition is degraded more severely than under the working bias condition during proton irradiation. This phenomenon is similar to that under the irradiation of gamma rays with a high dose rate.

Figure 6 shows the changes in supply current ($-I_{\rm S}$), with supply voltage at -5 V, of the AD9058 as a function of irradiation dose induced by protons with 1.11×10^3 rad/s dose rate. Based on the results in Fig. 6, it is obvious that the supply current of the AD9058 under the zero bias condition decreases with irradiation dose increasing. Moreover, under the working bias condition, the supply current increases with total dose increasing until 1.0×10^5 rad. Then, the supply current decreases with total dose increasing.

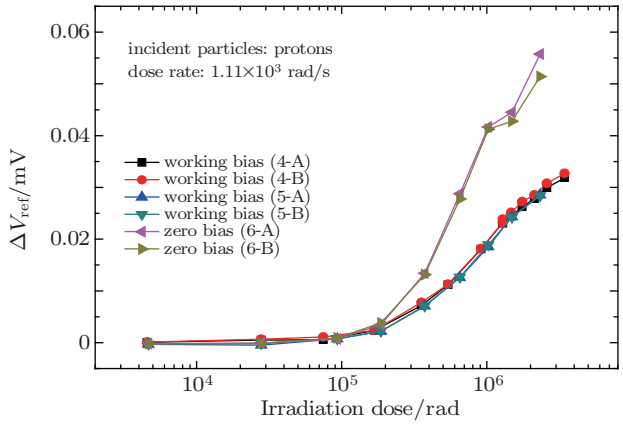


Fig. 5. (color online) Changes in reference voltage of the ADCs ($\Delta V_{\rm ref}$) as a function of irradiation dose, induced by 10-MeV proton irradiation.

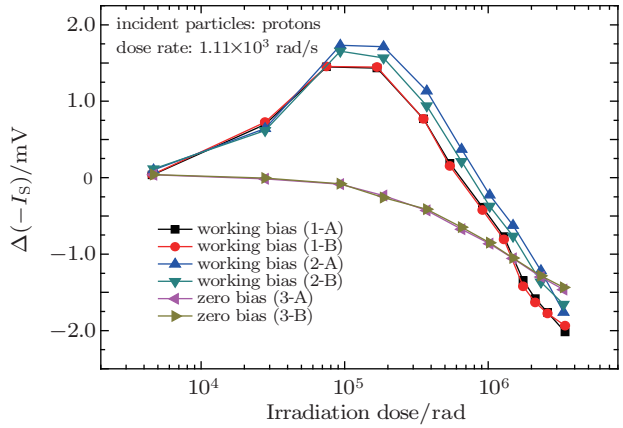


Fig. 6. (color online) Changes in ADC supply current ($\Delta(-I_{\rm S})$) as a function of irradiation dose, induced by 10-MeV proton irradiation.

Figure 7 shows the changes in output logic "0" voltage ($V_{\rm OL}$) of the AD9058 as a function of dose, induced by proton irradiation. Based on the results in Fig. 7, it is obvious that the output logic voltage of the AD9058 increases with irradiation dose increasing. Moreover, the output logic voltage under the working bias condition will be degraded more severely than under the zero bias condition during proton irradiation.

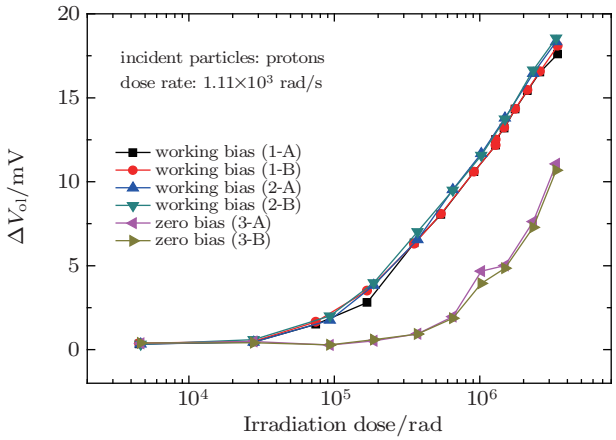


Fig. 7. (color online) Changes in output logic voltage of the ADCs ($\Delta V_{\rm ol}$) as a function of dose, induced by 10-MeV proton irradiation.

3.3. Discussion

Based on the results from Fig. 2 to Fig. 4, the ELDRS is shown obviously. For example, the degradations of reference voltage and supply current, during gamma ray irradiation, display different damage for various dose rates, which can be explained by the space charge model.[23,24] The trapped charges in the oxide layer and interface states between Si and SiO_2 layers can be produced during gamma ray irradiation. The higher the numbers of trapped charges and interface states, the more severe the degradation of the electrical parameter for AD9058 is. Especially, the number of interface states can be the main contributor to the degradation of an ADC. Based on the space charge model, compared with low dose rate, high dose rate can induce a great number of trapped charges in an oxide layer for AD9058 at a given irradiation time. These trapped charges induce a space field in the oxide layer, which could block off the holes and hydrogen, induced by irradiation, from arriving at the Si/SiO_2 interface and forming interface states. On the other hand, the low dose rate can induce many more interface states than a high dose rate at a given total dose, resulting in larger degradation of electrical parameter for AD9058 as shown in Figs. 2 and 4. However, the degradation of output logic voltage does not show ELDRS clearly. That is to say, the sensitivities of various electrical parameters to ELDRS are different for AD9058. This point needs further research.

Another phenomenon, the bias condition effect, is revealed clearly during gamma ray and proton irradiation as shown in Figs. 2–7. Based on the results, it is obvious that the degradations of supply current and output logic voltage are more severe under the working bias condition than under the zero bias condition at a given total dose, during both high and

low dose rate irradiation. However, the degradation of reference voltage is larger under the working bias condition during low dose rate irradiation, while it is small during high dose rate irradiation at a given total dose. These phenomena need to be further studied, and may be explained by the fringing field in the oxide layer.[25,26] The fringing field in the oxide layer will influence the distribution and transportation of the trapped charge induced by ionizing damage, leading to different degradations of electrical parameters for AD9058. The fringing field in the oxide layer is affected by the working or zero bias condition. The fringing field induced by the working bias condition can cause more severe degradation of the electrical parameter for AD9058.

In addition, the degradation of AD9058 does not display obvious ELDRS during 10-MeV proton irradiation. Comparing the results in Fig. 2 with those in Fig. 5, it is clear that the degradation of reference voltage, induced by 10-MeV proton irradiation, displays a high dose rate effect. The degradation of output logic voltage shows a similar result. Moreover, based on the results in Figs. 3 and 6, the supply current displays a different degradation trend induced by 10-MeV proton irradiation from that caused by gamma ray irradiation, for AD9058 under the working bias condition. This can be induced by displacement damage produced by 10-MeV protons. The 10-MeV proton can produce the primary knock-on atom (PKA) in the ADC. If the recoil energy of the PKA is large enough, the PKA will produce secondary displacements, creating a cascade of displacements.[27] All of these phenomena will create displacement defects, resulting in bulk damage to semiconductors, increasing the number of recombination centres and therefore reducing minority-carrier lifetime, and finally degrading the performance of an ADC. As mentioned above, the supply current may be sensitive to displacement defects for AD9058 under the working bias condition during 10-MeV proton irradiation.

4. Conclusions

The degradation of AD9058 is examined under the exposure to 10-MeV proton and gamma ray irradiation with various dose rates. From the experimental results, it is clear that the degradations of reference voltage and supply current display obvious ELDRS, while ELDRS is not found in the degradation of output logic voltage. In addition, compared with the zero bias condition during irradiation, the working bias condition will cause bigger degradations of supply current and output logic voltage at a given total dose. However, the contribution of bias condition to reference voltage is affected by dose rate. Compared with the zero bias condition, during low dose rate irradiation, the working bias condition will cause severe degradation of the reference voltage at a given total dose. On the other hand, the working bias condition can induce smaller degradation of the reference voltage than the zero bias condition at a given total dose during high dose rate irradiation. In addition, 10-MeV proton irradiation, with selected flux, can produce a high dose rate effect and displacement damage to the AD9058.

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