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A comparison of ionizing radiation damage in CMOS devices from ^{60}Co gamma rays, electrons and protons*

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Abstract Radiation hardened CC4007RH and non-radiation hardened CC4011 devices were irradiated using ^{60}Co gamma rays, 1 MeV electrons and 1—9 MeV protons to compare the ionizing radiation damage of the gamma rays with the charged particles. For all devices examined, with experimental uncertainty, the radiation induced threshold voltage shifts ($\Delta V_{\rm th}$) generated by ^{60}Co gamma rays are equal to that of 1 MeV electron and 1—7 MeV proton radiation under 0 gate bias condition. Under 5 V gate bias condition, the distinction of threshold voltage shifts ($\Delta V_{\rm th}$) generated by ^{60}Co gamma rays and 1 MeV electrons irradiation are not large, and the radiation damage for protons below 9 MeV is always less than that of ^{60}Co gamma rays. The lower energy the proton has, the less serious the radiation damage becomes.

Key words gamma rays, electrons, protons, radiation damage

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1 Introduction

For years, investigators performing radiation tests on CMOS devices have relied primarily on ^{60}Co generated gamma rays to simulate the natural space radiation environment[1—4]. A possible problem is that the natural space radiation environment consists mainly of high-energy protons and electrons, and not ^{60}Co gamma rays. Figs. 1 and 2 shows electron and proton energy distribution in the Van Allen radiation belts.

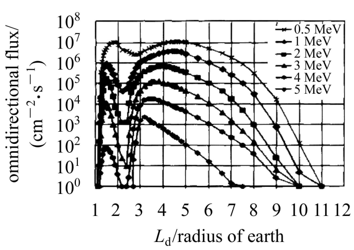

Fig. 1. Energy distribution in electron belt.

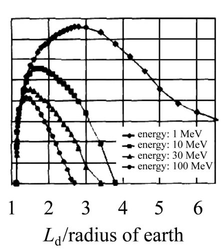

Fig. 2. Energy distribution in proton belt.

As a result, people doubted that the radiation effect produced by laboratory gamma rays in CMOS devices is equivalent to those produced by protons or electrons. Many scientists are focusing a lot of study in this field to resolve this problem. Therefore, a great deal of research results have been provided[5—7]. In this paper, CC4007RH and CC4011 devices are irradiated with ^{60}Co gamma rays, 1 MeV electrons and 1—9 MeV low-energy protons to compare the ionizing radiation damage of the gamma rays with the charged particles.

2 Samples and experiment

The objective of this experiment is to research the radiation induced failure responses of radiation hardened CC4007RH and non-radiation hardened CC4011 CMOS devices when exposed to gamma rays, 1—9 MeV low-energy protons and 1 MeV electrons. Ionizing radiation interacts with SiO_2 layers resulting in the generation of holes that are preferentially trapped near the Si-SiO_2 interface and the generation of interface states. These radiation induced effects cause threshold voltage shift ($\Delta V_{\rm th}$) and other unwanted changes in device characteristics. So, the irradiation samples were removed from different irradiation

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sources for threshold voltage shift measurement after irradiation.

I-V measurements of the experimental devices were taken within thirty minutes after irradiation by using are HP4156 semiconductor parametric analyzer controlled by a computer. The threshold voltage is defined as the voltage-axis intercept of the square root of the drain current versus gate voltage in saturation. Table 1 exhibits experimental CMOS devices' corresponding ray type and energy.

Table 1. Experimental CMOS devices' corresponding radiation ray type and energy.

ray type	radiation hardened CC4007RH devices	non-radiation hardened CC4011 devices
protons	2 MeV, 5 MeV, 7 MeV	2 MeV, 5 MeV, 9 MeV
electrons	1 MeV	1 MeV
γ-rays	90.2 rad(Si)/s	0.2 rad(Si)/s

γ-ray experiments are carried out on ^{60}Co sources at the Northwest Institute of Nuclear Technology. ^{60}Co γ-ray dose rate is measured by a universal dosemeter (UNIDOS).

Proton experiments are performed on the EN accelerator of the State Key Laboratory of Nuclear Physics and Technology, Peking University. The proton energy is 2, 5, 7 and 9 MeV and the corresponding ionizing dose rate is 300—1000 rad(Si)/s.

The 1 MeV electrons experiment is carried out on the accelerator of electrons at the Northwest Institute of Nuclear Technology. The 1 MeV electron dose rate is 1×10^4 rad(Si)/s.

The experimental samples keep two bias conditions during the radiation period.

(1) $V_{gs}=V_{dd}=5$ V, $V_{ss}=0$;

(2) $V_{gs}=V_{ss}=0$, $V_{dd}=5$ V.

V_{gs} is gate voltage, V_{ss} is ground and V_{dd} is power voltage.

3 Results and discussion

3.1 A comparison of radiation damage in the CC4007RH devices from different sources under different gate bias conditions

Figure 3 demonstrates the experimental results for radiation hardened CC4007RH devices from ^{60}Co gamma rays, 1 MeV electrons and 5 MeV protons irradiation under $V_{gs} = V_{dd} = 5$ V, $V_{ss} = 0$ and $V_{gs} = V_{ss} = 0$, $V_{dd} = 5$ V radiation conditions. Fig. 3(a) and (b) are plots of ΔV_{th} versus radiation dose for CC4007RH-NMOS and CC4007RH-PMOS respectively. The result in Fig. 3 shows that under 0 gate bias conditions, the threshold voltage shifts for CC4007RH-NMOS at 2×10^5 rad(Si) irradiation dose from 1 MeV electrons, ^{60}Co gamma rays and 5 MeV protons resource are −0.50, −0.46 and −0.51 V, respectively. The threshold voltage shifts for CC4007RH-PMOS at 2×10^5 rad(Si) irradiation dose from 1 MeV electrons, ^{60}Co gamma rays and 5 MeV protons resource are −0.28, −0.29 and −0.19 V, respectively. That is, for equal absorbed dose, the 1 MeV electrons, ^{60}Co gamma rays and 5 MeV protons produced nearly the same radiation damage on the CC4007RH devices with experimental uncertainty. However, under 5 V gate bias conditions, the radiation damage from the ^{60}Co gamma rays is greater than 1 MeV electrons and 5 MeV protons for equal absorbed dose. The threshold voltage shift produced at 2×10^5 rad(Si) irradiation dose from ^{60}Co gamma rays for NMOS devices is about −1.50 V, and about −1.15 V for PMOS devices. Therefore, for equal absorbed dose, the damage produced by 1 MeV electrons and 5 MeV protons is equivalent to the ^{60}Co gamma ray damage under 0 gate bias conditions.

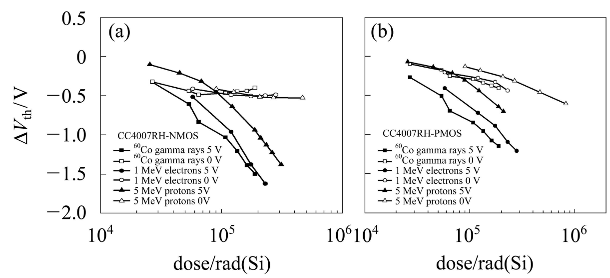

Fig. 3. ΔV_{th} versus radiation dose from ^{60}Co gamma ray, 1 MeV electron and 5 MeV proton radiation under different gate bias conditions for (a) CC4007RH-NMOS devices and (b) CC4007RH-PMOS devices.

Figure 4 demonstrates the experimental results for radiation hardened CC4007RH devices from 2 and 5 MeV proton irradiation under $V_{gs} = V_{dd} = 5$ V, $V_{ss} = 0$ and $V_{gs} = V_{ss} = 0$, $V_{dd} = 5$ V bias conditions. The result in Fig. 4 shows the threshold voltage shift for CC4007RH devices related to proton energy and gate bias conditions. Under 5 V gate bias conditions, the radiation damage is directly proportional to the proton energy. That is, the higher the proton energy, the greater the damage. However, under 0 gate bias conditions, the threshold shifts for NMOS devices at 2×10^5 rad(Si) dose from 2 MeV and 5 MeV proton irradiation are about −0.57 V and −0.59 V. The radiation damage from 2 MeV and 5 MeV protons is equivalent. For equal absorbed dose, under 0 V gate bias conditions, the damage produced by different energy protons is equivalent.

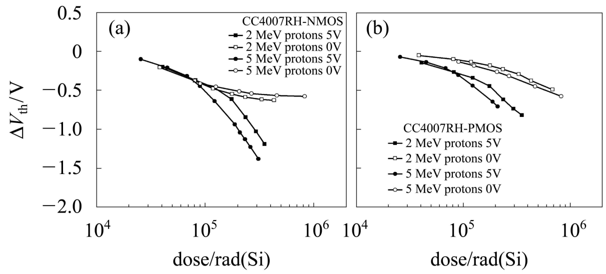

Fig. 4. $\Delta V_{\rm th}$ versus radiation dose from 2 MeV and 5 MeV proton radiation under different gate bias condition for (a) CC4007RH-NMOS devices and (b) CC4007RH-PMOS devices.

3.2 A comparison of radiation damage from different sources under $V_{\rm gs} = V_{\rm dd} = 5$ V, $V_{\rm ss} = 0$ V conditions

Figures 5 and 6 demonstrate the experimental results for radiation hardened CC4007RH and non-radiation hardened CC4011 respectively from ^{60}Co gamma ray, 1 MeV electron and 1—9 MeV proton irradiation under $V_{\rm gs} = V_{\rm dd} = 5$ V, $V_{\rm ss} = 0$ bias conditions. The radiation hardened CC4007RH exposed to ^{60}Co gamma ray dose rate is 90.2 rad(Si)/s, and non-radiation hardened CC4011 exposed to ^{60}Co gamma ray dose rate is 0.2 rad(Si)/s.

Let us compare the radiation damage effect for ^{60}Co gamma rays and 2—9 MeV protons in Figs. 5 and 6. Fig. 5 shows that under 5 V gate bias conditions, the threshold voltage shifts for CC4011-NMOS devices are −0.96, −1.77 and −2.72 V at proton energies of 2, 5, and 9 MeV, respectively. The radiation damage is directly proportional to the proton energy. That is, the higher the proton energy, the more the damages. The higher energy protons have the higher accumulation flux. So, the damage is more serious. The radiation damage induced from below 7 MeV protons for CC4007RH devices is less than that of ^{60}Co gamma rays. The results in Fig. 6 show that the radiation damage induced from below 9 MeV protons for CC4011 device is also always less than ^{60}Co gamma rays, but the damage induced from 9 MeV protons is greater than ^{60}Co gamma rays.

Let us compare the radiation damage effect for ^{60}Co gamma rays and 1 MeV electrons in Figs. 5 and 6. Under 5 V gate bias conditions, the threshold voltage shift induced by ^{60}Co gamma rays is greater than the 1 MeV electrons, but the distinction between the 1 MeV electrons and the ^{60}Co gamma rays is not large. The reason is that the energy of ^{60}Co gamma rays is 1.17 MeV and 1.33 MeV. The main interaction between photons and SiO_2 is Compton scattering. In the Compton process, most of the photon energy is carried away by the secondary electrons, and these electrons deposit almost all the energy deposited in SiO_2. The energy of Compton secondary electrons is approximately 1 MeV. Therefore, the radiation damage induced by ^{60}Co gamma rays and 1 MeV electrons is equivalent within the limit of error.

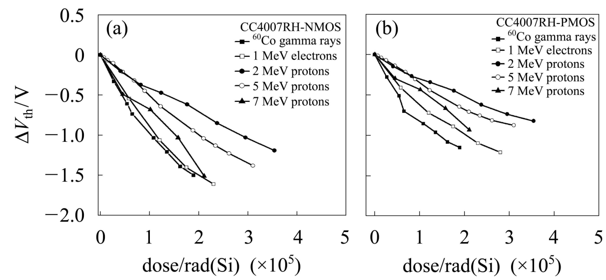

Fig. 5. $\Delta V_{\rm th}$ versus radiation dose from ^{60}Co gamma ray, 1 MeV electron and 2—7 MeV proton radiation under 5 V gate bias condition for (a) CC4007RH-NMOS devices and (b) CC4007RH-PMOS devices.

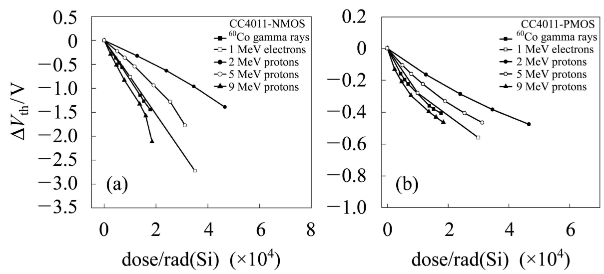

Fig. 6. $\Delta V_{\rm th}$ versus radiation dose from ^{60}Co gamma ray, 1 MeV electron and 2—9 MeV proton radiation under 5 V gate bias condition for (a) CC4011-NMOS devices and (b) CC4011-PMOS.

3.3 Comparison of the damage sensitivity from ^{60}Co gamma rays, electrons and protons

Usually, the level of radiation damage is expressed by the damage sensitivity, $\Delta V_{\rm th}$/dose. The level of radiation damage relates to the ionizing radiation dose, but the radiation damage induced by different sources is not the same. Table 2 demonstrates the comparison of the damage sensitivity from different radiation sources for radiation hardened CC4007RH devices under 5 V gate bias condition. Table 3 demonstrates a comparison of the damage sensitivity from different radiation sources for non-radiation hardened CC4011 devices under 5 V gate bias condition. The energy of ^{60}Co gamma rays is 1.17 and 1.33 MeV, so the average energy is 1.25 MeV.

Table 2. Comparison of the damage sensitivity from ^{60}Co gamma rays, 1 MeV electrons and 2—7 MeV protons.

type of radiation sources	energy/MeV	device type	damage sensitivity V/krad	compared with ^{60}Co
^{60}Co γ-rays	1.25	NMOS	0.0100	1.0
		PMOS	0.0083	1.0
electrons	1	NMOS	0.0083	0.83
		PMOS	0.0055	0.66
protons	2	NMOS	0.0039	0.39
		PMOS	0.0028	0.34
	5	NMOS	0.0047	0.47
		PMOS	0.0031	0.37
	7	NMOS	0.0078	0.78
		PMOS	0.0049	0.59

Table 3. Comparison of the damage sensitivity from ^{60}Co gamma rays, 1 MeV electrons and 2—9 MeV protons.

type of radiation sources	energy/MeV	device type	damage sensitivity V/krad	compared with ^{60}Co
^{60}Co γ-rays	1.25	NMOS	0.082	1.0
		PMOS	0.029	1.0
electrons	1	NMOS	0.077	0.94
		PMOS	0.023	0.79
protons	2	NMOS	0.027	0.33
		PMOS	0.011	0.38
	5	NMOS	0.049	0.60
		PMOS	0.018	0.61
	9	NMOS	0.107	1.30
		PMOS	0.036	1.23

The data of Tables 2 and 3 shows that under 5 V gate bias conditions, the damage sensitivity of ^{60}Co gamma rays is the most serious, the damage sensitivity of protons below 9 MeV is less than that of ^{60}Co, and the damage distinction between the 1 MeV electrons and the ^{60}Co gamma rays is not big. The radiation damage is directly proportional to the proton energy; the higher the proton energy, the larger the damage. The experimental result presented here is in agreement with the published data[6, 7].

The experiments have confirmed that proton damage is energy and bias dependent. Therefore, the radiation sources of CMOS devices on ground experiments are often performed either with ^{60}Co or electrons. But ^{60}Co irradiation is a reliable worst-case simulation for the natural space radiation environment.

4 Conclusions

For the CMOS device tested, the radiation damage effect induced from ^{60}Co gamma rays, 1 MeV electrons and 1—7 MeV protons is equivalent under 0 gate bias conditions. However, the radiation damage for ^{60}Co gamma rays is most serious under 5 V gate bias conditions. The damage distinction between 1 MeV electrons and ^{60}Co gamma rays is not big. Under 5 V gate bias conditions, the radiation damage is directly proportional to the proton energy. The damage for protons below 9 MeV is always less than ^{60}Co. The lower the proton energy is, the less the damage. ^{60}Co irradiation is a reliable worst-case simulation for the natural space radiation environment.

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