Synergistic effects of neutron and gamma ray irradiation of a commercial CHMOS microcontroller

Jin Xiao-Ming(金晓明)[a)†], Fan Ru-Yu(范如玉)[a)b)], Chen Wei(陈 伟)[b)], Lin Dong-Sheng(林东生)[b)], Yang Shan-Chao(杨善潮)[b)], Bai Xiao-Yan(白小燕)[b)], Liu Yan(刘 岩)[b)], Guo Xiao-Qiang(郭晓强)[b)], and Wang Gui-Zhen(王桂珍)[b)]

[a)] *Department of Engineering Physics, Tsinghua University, Beijing* 100084, *China*
[b)] *Northwest Institute of Nuclear Technology, Xi'an* 710024, *China*

(Received 8 August 2009; revised manuscript received 7 January 2010)

This paper presents the experimental results of a combined irradiation environment of neutron and gamma rays on 80C196KC20, which is a 16-bit high performance member of the MCS96 microcontroller family. The electrical and functional tests were made in three irradiation environments: neutron, gamma rays, combined irradiation of neutron and gamma rays. The experimental results show that the neutron irradiation can affect the total ionizing dose behaviour. Compared with the single radiation environment, the microcontroller exhibits considerably more severe degradation in neutron and gamma ray synergistic irradiation. This phenomenon may cause a significant hardness assurance problem.

Keywords: total ionizing dose, neutron irradiation, synergistic effect, microcontroller

PACC: 6180, 7340Q

1. Introduction

With the pervasive application of commercial-off-the-shelf microelectronics in spacecraft, to achieve increased system performance, an estimation of the sensitivity to radiation of a device or architecture is a mandatory step to gain an insight about the impact of radiation on the level of reliability. The effects of atomic displacement and the total ionizing dose (TID) induced by trapped particles are responsible for the electrical and functional failure of the applied, very large, scale integrated circuits.[1] In radiation ground accelerated tests, the TID effect is usually decoupled from displacement damage, assuming that these two effects are independent of each other.[2] This assumption may neglect the interaction between different radiation effects and would lead to a misestimate of radiation tolerance. It is reported that the neutron exposure may significantly affect the subsequent TID degradation.[3−5] It is necessary to take this synergistic effect into consideration.

Typically, previous literature showed that the most sensitive parameters were the standby current and the operating supply current during irradiation. These parameters were considered to be the most critical ones in practical applications as the system could only provide limited power to the microprocessor. Moreover, they generally focused on the TID effect but ignored the influence of the displacement effect on the ionizing effect.[6] In this paper, we conduct completely electrical and functional parameters tests in the single and mixed neutron and gamma ray irradiation environment, based on the mechanism understanding of the radiation effect on complementary high-performance metal oxide semiconductor (CHMOS) technology. The output voltage shift of a certain module is also one of the sensitive parameters other than the static power supply current. The experimental results indicate that the microcontroller will show much faster degradation when exposed to the combined neutron and gamma ray environment, and the synergistic effect is an accelerated TID effect.

2. Description of test

The 80C196KC20 is a commercial 16-bit microcontroller that is pin equivalent to the MCS-96 industrial standard microcontroller when used in a 68-pin plastic leaded chip carrier (PLCC). The microcontroller is fabricated using the Intel CHMOS process and its static design allows operation from 1 to 20 MHz. No radiation hardness guarantee or radiation performance characteristics are provided by the

†Corresponding author. E-mail: jxm02@mails.thu.edu.cn
© 2010 Chinese Physical Society and IOP Publishing Ltd

manufacturer.

The experimental test system is mainly composed of an 80C196KC20, a LM7805, an 74LS373 and an AT28C256. In addition, we design a data collection system based on the monolithic integrated circuit serial port communication. The LM7805 is an integrated liner positive voltage regulator which offers a fixed supply voltage 5 V for the other chips. The 74LS373 is an octal transparent latch which latches the low 8-bit address data because the microcontroller has multiplexed address/data bus. The AT28C256 is a high performance electrically erasable and programmable read-only memory (EEPROM) which is used for storing the programme and the data. The microcontroller reads and executes instructions programmed into the EEPROM beforehand with the EA (external access) pin strapping to Vss (ground) to cause memory accessible to locations 2000H through 5FFFH to be directed to off-chip memory. The serial port communication is a practical means of transmitting data between the microcontroller and the personal computer.

In order to study the radiation effect of 80C196KC20, a comprehensive set of electrical and functional parameters has been measured using the above-mentioned system. The power supply current of the microcontroller is monitored during each irradiation experiment. Moreover, the microcontroller circuit is split into six different blocks:

(i) The internal clock generator: The oscillator frequency of the oscillator inverter and the internal clock generator is 11 MHz. The frequency of output of the internal clock generator (CLKOUT) is 1/2 of the oscillator frequency. Tests at different clock rates showed that clock frequency has little effect on radiation degradation in previous literature.[6]

(ii) Intelligent 16-bit timer: This timer is an automatic arithmometer which takes 8 clock cycles to increase one and then overflows and causes an interrupt programme in which we reverse the output of IO port1. So each pin of IO port1 exports a square waveform with a frequency 5.3 Hz.

(iii) Data memory: The microcontroller implements 512 bytes of internal data random access memory (RAM). The first 24 bytes of this RAM are reserved for the special function registers (SFRs). We test its high-speed read and write capability.

(iv) Central processing unit (CPU): We program a series of operational and logical instructions read and executed by the microcontroller to test the processing capability of the CPU, including adding, subtracting, comparing, multiplying, dividing, logical AND, logical NOT, logical OR, logical XOR, logical CLEAR and shift instructions.

(v) Pulse width modulation (PWM): We configure the PWM register and the PWM pin output a square waveform with a period of 46 μs, which equals 255 clock cycles.

(vi) A/D converter: The microcontroller has a 10-bit analog/digital (A/D) converter which is ratiometric and the absolute accuracy is dependent on the accuracy and stability of V_{REF} pin. The V_{REF} pin is connected to a steady input voltage 5 V and the ACH3 pin is imported with a settled input voltage 2.5 V as the analog signal. With appropriate configuration, we test the AD result register to monitor the capability of AD transfer.

The waveforms of CLKOUT, IO port and PWM are measured by oscillograph while the results of AD converter, RAM access ability and CPU processing capability are transmitted to the personal computer by the serial communication. In this paper we only consider those most sensitive parameters.

The irradiation experiments were carried out at room temperature in the Northwest Institute of Nuclear Technology, China. The TID exposure was performed using a Co-60 irradiator with a dose rate of 20 rad(Si)/s. Neutron exposure and synergistic irradiation of neutron and gamma rays were performed using a nuclear reactor in different states. The ratio of neutron flux and gamma dose rate (n/γ) is 6.1×10^9 n/cm$^2\cdot$rad (Si) in the neutron irradiation environment and 3.3×10^8 n/cm$^2\cdot$rad (Si) in the synergistic irradiation environment. The neutron energy is distributed between 10 keV and 10 MeV and the mean value of the neutron energy is about 1 MeV. In the higher n/γ irradiation the neutron radiation effect dominates, so the TID effect induced by parasitic gamma rays can be ignored. The peripheral circuit is separated from the device under test in the printed circuit board and is shielded.

3. Test results and discussion

3.1. TID effect

Generally speaking, TID could induce a shift in the threshold voltage and a large increase in static power supply current caused by electrostatic effect of trapped charge and charged interface traps in MOS

technological integrated circuits.[7,8] Therefore, it is somewhat expected that the leakage current and the voltage of waveforms of commercial CHMOS microcontroller should exhibit significant variation under TID test.

Figure 1 shows the static power supply current as a function of the total ionizing dose. The static power supply current exhibits the highest total ionizing dose degradation and is the first parameter that fails the specification. The static power supply current does not increase until the TID reaches 8.0 krad (Si). After the increase of the static power supply current, the microcontroller fails to run the programme in the external EEPROM at the dose level of 11.3 krad (Si). At the same time, the functions based on the serial communication could not be tested anymore.

Besides the increase of the static power consumption, the waveforms exhibit significant degradation after the functional failure. Figure 2 shows the pronounced effect on the IO port and PWM outputs. Actually, the outputs of the IO port are fixed to a DC voltage from an AC signal at the TID of 11.3 krad (Si), when the microcontroller fails to run, the timer overflow interrupts the program in which we have reversed the output. Subsequently, the DC voltages of the IO port outputs are shifted during the accumulation of TID, which is shown in Fig. 3. The high-level voltage decreases remarkably, while the low-level voltage increases appreciably. Meanwhile, figure 2 shows that the PWM exhibits a similar degradation to the IO port but finally degenerates to a fixed voltage because the clock generator could not provide a usable frequency clock at a dose level of 46.6 krad (Si). Figure 4 shows the amplitude and low-level voltage of the PWM versus the TID. The amplitude drops significantly during the gamma ray irradiation, while the low-level voltage rises slightly. The PWM waveform is fixed to a DC voltage at the TID of 46.6 krad (Si), when the internal clock generator of the microcontroller fails to generate a clock signal.

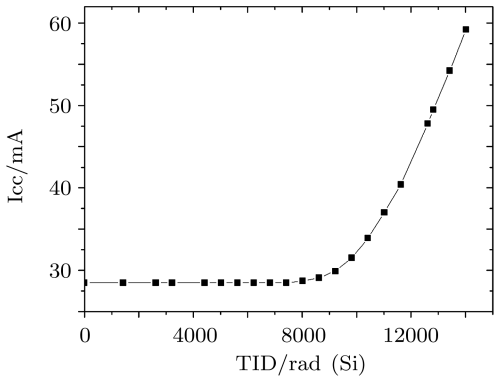
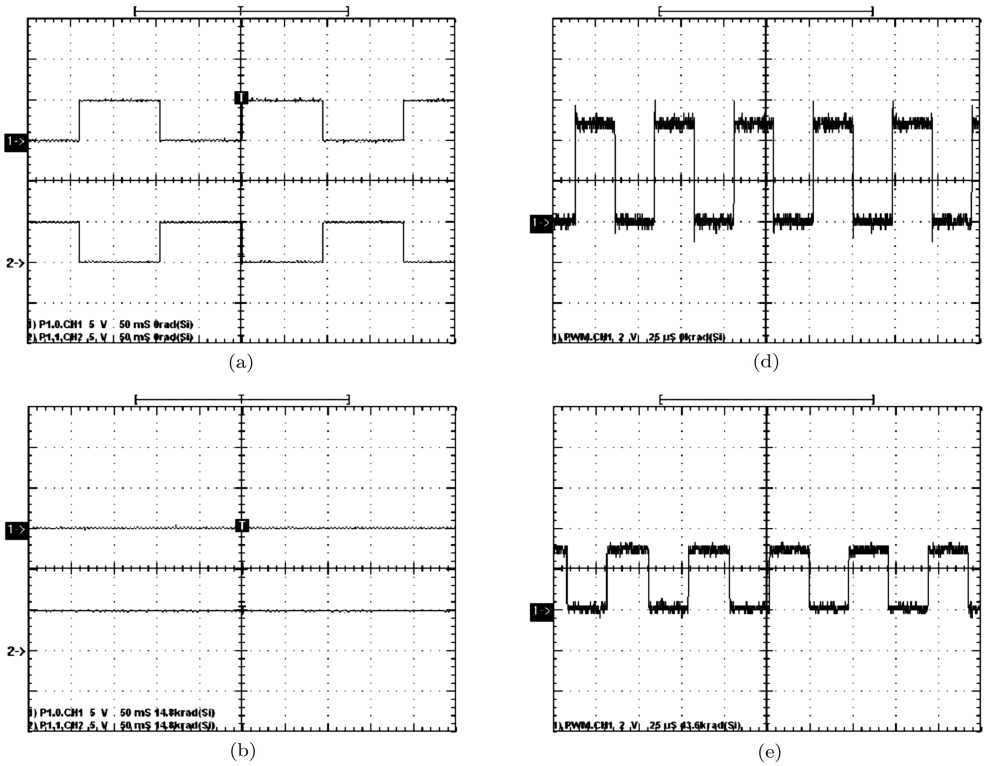


Fig. 1. Icc versus total ionizing dose in TID effect test.



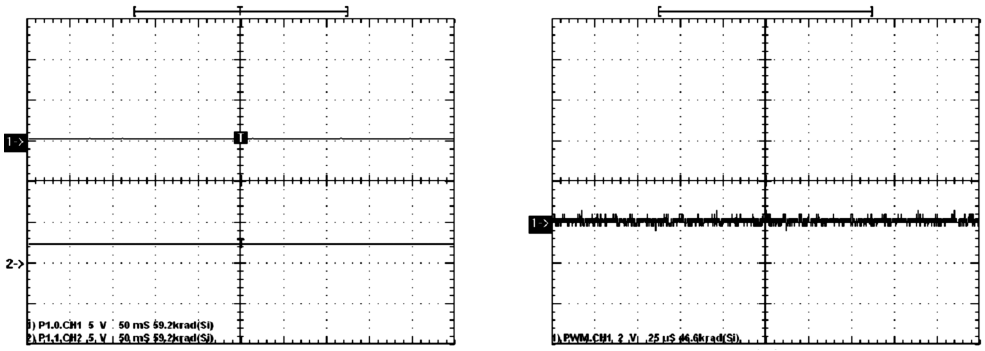


Fig. 2. The change of the IO port and PWM waveforms in the TID effect test. The three figures on the left show the change of the IO port waveform at different ionizing doses, (a) 0 krad (Si), (b) 14.8 krad (Si), (c) 59.2 krad (Si). The three figures on the right show the change of the PWM waveform at different ionizing doses, (d) 0 krad (Si), (e) 43.6 krad (Si), (f) 46.6 krad (Si).

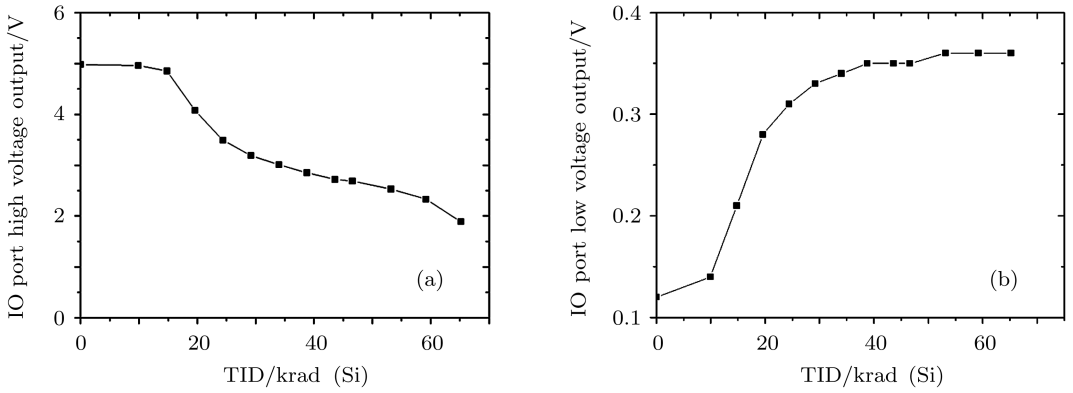


Fig. 3. The voltage shift of the IO port versus TID in TID effect test.

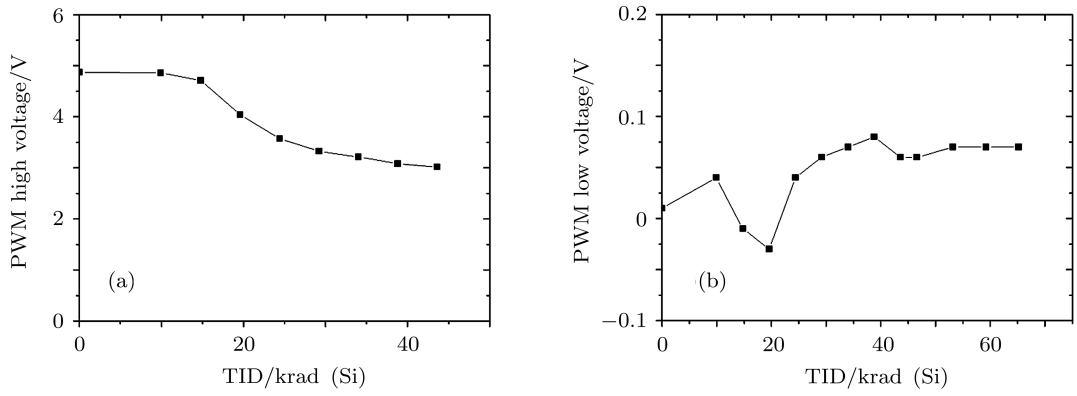


Fig. 4. The amplitude and low-level voltage shift of the PWM versus TID in TID effect test.

3.2. Neutron radiation effect

Under the single neutron irradiation environment of the nuclear reactor, the ionizing effect of the neutron on the microcontroller manufactured by CHMOS technology can be neglected while the displacement effect could induce a decrease of the density, lifetime and mobility ratio of the charge carrier. But generally speaking, CHMOS technology exhibits a high-level tolerance of neutron.

We have performed the neutron radiation effect test using two samples biased and another two samples unbiased. The total neutron fluence was up to 3.0×10^{13} n/cm^2. During the neutron irradiation the

functional failure was observed in the biased samples. The RAM data presented mistakes and the logical instructions were executed mistakenly. The microcontroller failed to run after a time interval, but fortunately we could reset the microcontroller to make it operate again. Figure 5 shows the static power supply current as a function of the neutron fluence. The current decreases slowly and almost linearly. This result is not surprising according to the testing result and analysis reported in Ref. [9]. It is believed that the decrease of the density and mobility of the charge carrier leads to the decrease of the static power consumption. The unbiased samples were tested 10 days later and all the electrical and functional parameters did not have significant changes. Then the samples were exposed to gamma rays to investigate the impact of the displacement effect on the TID effect. The results will be presented in the next section.

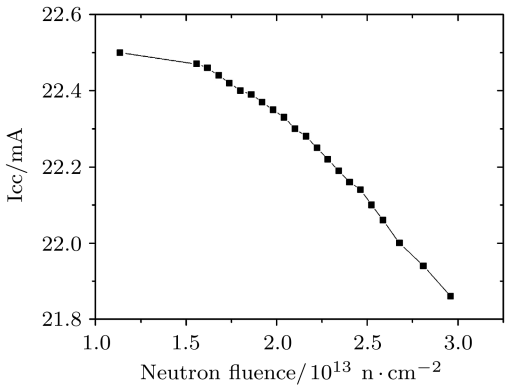


Fig. 5. Icc versus neutron fluence in neutron irradiation test.

3.3. Synergistic effect of neutron and gamma rays

In this subsection we emphasize the differences between the TID effect and the synergistic effect, since the single neutron environment only has little influence on the results. During the combined irradiation of neutron and gamma rays, the microcontroller exhibited an extremely significant degradation. The synergistic effect seems to be a similar but overly accelerated TID effect. Compared with the gamma ray radiation, all of the electrical and functional parameters failed earlier versus the TID. In order to further investigate the impact of the displacement defect on the TID effect, we have performed an additional experiment. Two samples were first unbiased and irradiated with neutron fluence up to 3.0×10^{13} n/cm^2 and then biased and exposed to gamma rays. Considering the parasitical gamma rays in the neutron radiation environment, we took a parallel experiment in which two samples were first unbiased and irradiated with gamma rays up to 5.0 krad (Si) and then biased and exposed to gamma rays.

Figure 6 shows the leakage current as a function of the TID in gamma radiation, combined radiation and two additional experiments. One of the curves marked with TID only in this graph is the same data plotted in Fig. 1. Each of the leakage currents increases nonlinearly after a specific jump-off point. In this graph, we can see an increased sensitivity for the mixed neutron and gamma irradiation parts. The samples exposed to the synergistic irradiation degrade more than the other samples and exhibit a greater increase in the TID sensitivity. The curves marked with N+TID show that the neutron radiation would bring forward the failure of the subsequent TID exposure, though the curves marked with TID+TID show that advanced gamma radiation induces a similar but weaker influence in the subsequent TID exposure. The leakage current is an important sensitive electrical parameter and can predict the failure of the microcontroller, so the synergistic irradiation indeed brings further significant damage in CHMOS large scale integrated circuits.

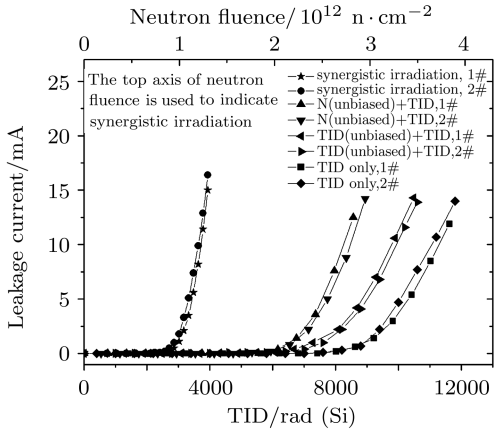


Fig. 6. Comparison of the leakage current in different experiments. The neutron fluence indicated on the graph is equivalent to the fluence of 1-MeV neutron.

Figure 7 shows the degradation of waveforms of the IO port and PWM during the radiation of combined neutron and gamma rays. It is indicated that these waveforms exhibit a similar degradation process compared with the TID effect. Figure 8 shows the high-level and low-level voltages of the IO port as functions of neutron fluence and TID, and a comparison with the TID effect, while figure 9 shows the amplitude

and low-level voltage of the PWM. The curves marked with TID only in Figs. 8 and 9 are the same data plotted in Figs. 3 and 4. From these two graphs, the voltage shifts exhibit the same qualitative behaviour as those in the samples exposed to TID only. Moreover, compared with TID effect, we see an accelerated degradation during synergistic irradiation, especially from the high-level voltage of IO port and the amplitude of PWM.

In summary, we can see the influence of the synergistic effect from the below-mentioned three aspects. First, the static power supply current begins to increase at the TID of 8.0 krad (Si) in the single gamma ray irradiation environment, while in the mixed irradiation environment it begins to increase at the TID of 2.3 krad (Si) and the neutron fluence of

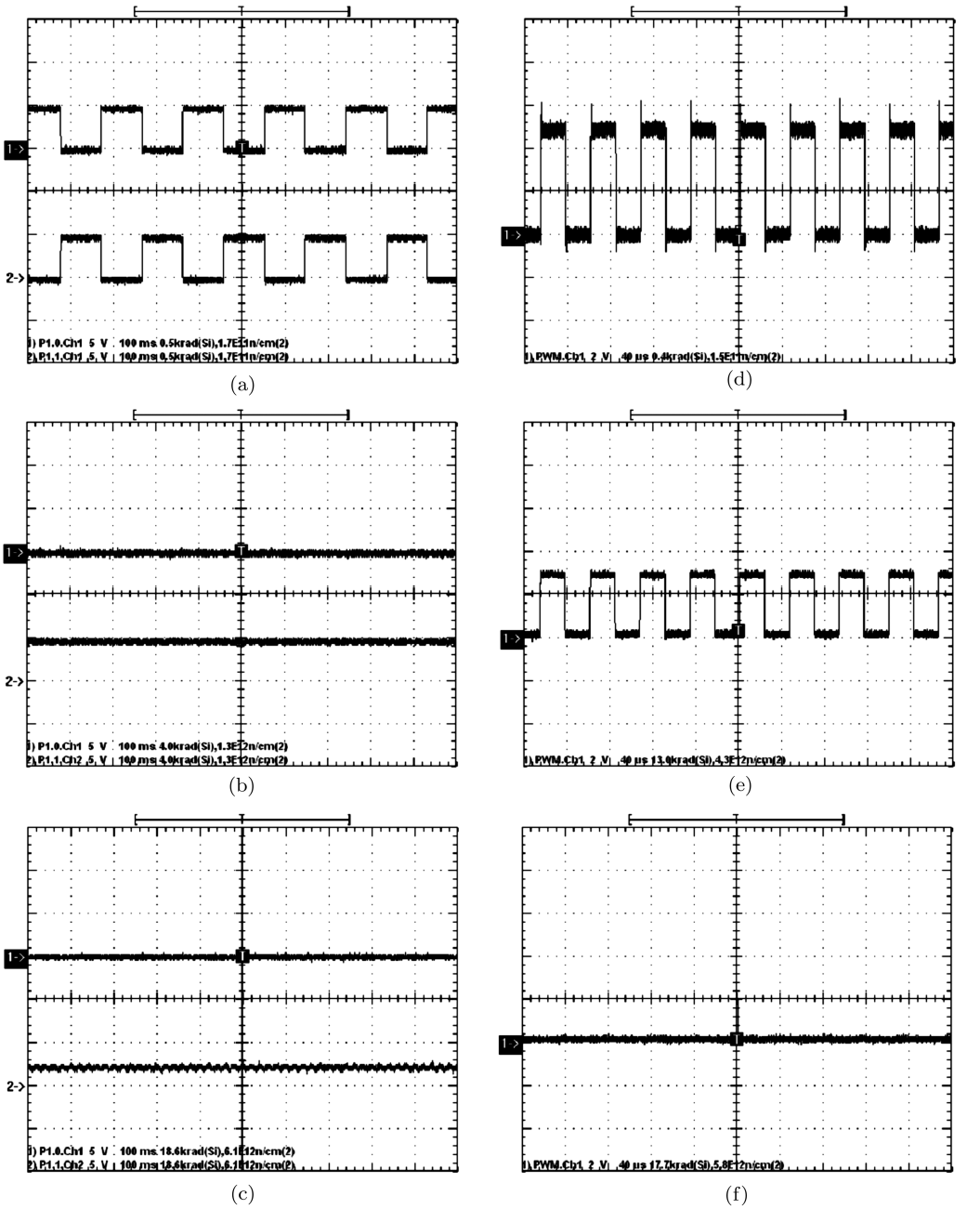


Fig. 7. The change of the IO port and PWM waveforms in the synergistic effect test. The three figures on the left show the change of the IO port waveform at different ionizing doses and neutron fluence. (a) 0.5 krad (Si), 1.7×10^{11} n/cm^2, (b) 4.0 krad (Si), 1.3×10^{12} n/cm^2, (c) 18.6 krad (Si), 6.1×10^{12} n/cm^2. The three figures on the right show the change of the PWM waveform at different ionizing doses and neutron fluence. (d) 0.4 kad (Si), 1.5×10^{11} n/cm^2, (e) 13.0 krad (Si), 4.3×10^{12} n/cm^2, (f) 17.7 krad (Si), 5.8×10^{12} n/cm^2.

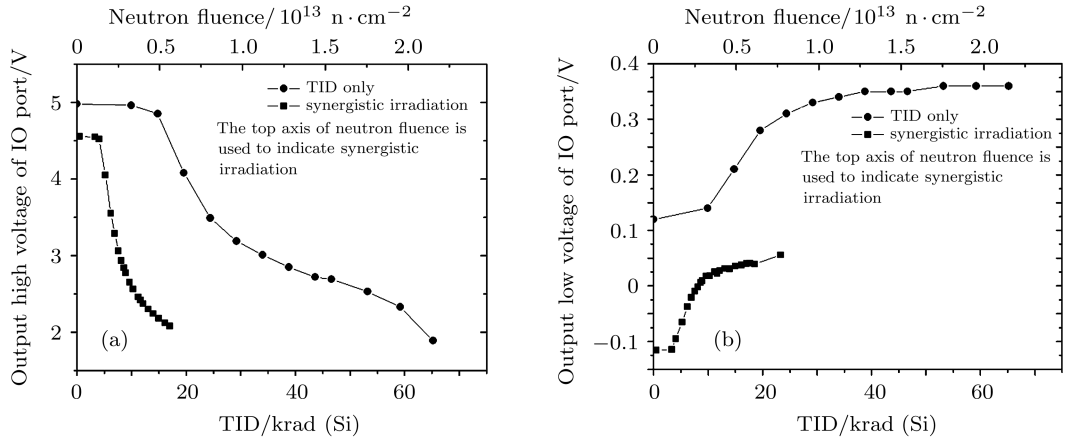


Fig. 8. The voltage shift of the IO port in the synergistic effect and TID effect.

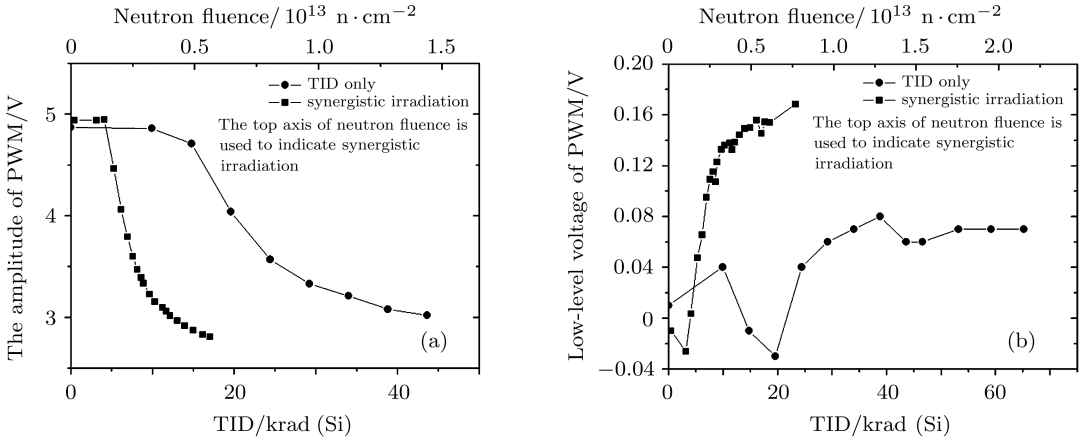


Fig. 9. The voltage shifts of the PWM in the synergistic effect and TID effect.

7.5×10^{11} n/cm^2. Second, when the microcontroller fails to run, the neutron fluence is approximately 1.2×10^{12} n/cm^2 and the TID is 3.7 krad (Si). As mentioned above, the microcontroller does not fail until the TID exposure accumulates up to 11.3 krad (Si), and performs normally even when the neutron fluence is up to 3.0×10^{13} n/cm^2. Third, when the internal clock generator fails to provide a clock signal, the TID is 46.6 krad (Si) in the single gamma ray irradiation environment, while the TID is 17.7 krad (Si) and the neutron fluence is 5.8×10^{12} n/cm^2 in the combined irradiation environment. Therefore, we can draw the conclusion that the microcontroller exhibits a very low level tolerance of the synergistic irradiation of neutron and gamma rays.

The degradation in the combined neutron and gamma ray irradiation environment presents an accelerated TID effect. The experimental results indicate that the synergistic effect is mainly attributed to the electrostatic effect of the oxide-trap charge and the interface-trap charge, which cause the subsequent leakage current and voltage shift, similar to the TID effect. The displacement effect induced by neutron irradiation may be responsible for the enhancement of the ionizing effect in CHMOS technology.

4. Conclusion

The synergistic irradiation results of the neutron and gamma ray test on a commercial CHMOS microcontroller show a similar response to the samples with gamma ray irradiation only, but much larger shifts on the electrical and functional parameters are observed. The electrical characteristics of the microcontroller, such as leakage current and voltage shift, as well as the functional failure, exhibit a significant accelerated degradation under the synergistic irradiation. There might be an interaction between the dis-

placement effect and the ionizing effect in CHMOS technology. Since the synergistic effect presents an accelerated TID effect, the displacement damage induced by neutron irradiation might accelerate the accumulation of the oxide-trap charge and the interface-trap charge induced by gamma ray irradiation. In this case, we cannot only investigate each single radiation effect, but we need to also perform an appropriate synergistic irradiation test. Therefore, it is necessary to evaluate the radiation tolerance accurately when similar integrated circuits are applied to a multiple radiation environment.

References

[1] Schrimpf R D 2007 *Radiation Effects on Embedded Systems* (Netherlands: Springer) p. 11

[2] Raymond J and Peterson E 1987 *IEEE Trans. Nucl. Sci.* **34** 1622

[3] Gorelick J L, Ladbury R and Kanchawa L 2004 *IEEE Trans. Nucl. Sci.* **51** 3679

[4] Brichard B, Brogermans P, Fernandez A, Lammens K and Decréton M 2001 *IEEE Trans. Nucl. Sci.* **48** 2069

[5] Chang J Y, Badawi M H and DeCicco A 1989 *IEEE Trans. Nucl. Sci.* **36** 2068

[6] Shaw D C and Lee C I 1995 *IEEE NSREC Workshop Record* Madison, WI, USA p. 60

[7] Chen W H, Du L, Zhuang Y Q, Bao J L, He L, Zhang T F and Zhang X 2009 *Acta Phys. Sin.* **58** 4090 (in Chinese)

[8] He B P, Chen W and Wang G Z 2006 *Acta Phys. Sin.* **55** 3546 (in Chinese)

[9] Xu T R and Yang H M 2005 *High Power Laser and Particle Beams* **17** 756 (in Chinese)