Synergistic effects of total ionizing dose on single event upset sensitivity in static random access memory under proton irradiation*

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Synergistic effects of the total ionizing dose (TID) on the single event upset (SEU) sensitivity in static random access memories (SRAMs) were studied by using protons. The total dose was cumulated with high flux protons during the TID exposure, and the SEU cross section was tested with low flux protons at several cumulated dose steps. Because of the radiation-induced off-state leakage current increase of the CMOS transistors, the noise margin became asymmetric and the memory imprint effect was observed.

Keywords: single event upset, total dose, static random access memory, imprint effect

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1. Introduction

According to the research, 45% of the failures of aerospace devices in the space radiation environment are caused by radiation-induced degradation in the electrical systems,[1,2] meanwhile, the single event upset (SEU) and the total ionizing dose (TID) are the main effects of radiation for CMOS devices.[3,4] In the space radiation environment, the aerospace devices are working under the SEU and the TID effects at the same time.[5] When the electrical systems of the devices degrade due to the total ionizing dose but do not actually cause any functional error, the SEU cross section could increase by 1–3 orders due to the potential TID damage.[6]

Since the 1980s, there have been some investigations on the synergistic effects of TID on SEU in static random access memories (SRAMs). Campbell[7] studied by using 40 MeV protons and pointed out that the SEU cross section would increase with increasing TID. Matsukawa[8] studied the threshold voltage shift of MOS transistors by using heavy ions and pointed out that the SEU cross section of PMOS increases while that of NMOS decreases with increasing TID. Some investigations[9–11] showed that the synergistic effects of TID on SEU sensitivity were related to the feature size of the devices and the test patterns during the exposure experiments. For the submicron or larger feature size devices, the imprint effect was shown; for the deep-submicron or smaller feature size devices, some showed the imprint effect, while some others showed the opposite experimental result of a con-imprint effect.

In summary, the synergistic effects between TID and SEU sensitivity have been observed for several decades and the investigations showed different results for different size devices and different test patterns.

In this work, we focus on the synergistic effects of TID on SEU in 0.18-μm and 0.25-μm SRAMs by using protons, and different test patterns are applied during the proton exposure. The TID-induced trend of the SEU sensitivity is obtained and the radiation damage mechanism is analyzed theoretically.

2. Experimental details

The details of the test devices are listed in Table 1. The test devices have been studied for the synergistic effect by using ^{60}Co gamma rays and high linear energy transfer (LET) heavy ions, and the con-imprint effect was observed.[12] In addition, we have the detailed internal construction of the test devices, which is useful to the 3D numerical simulation in the future.

Table 1. Test devices.

Device type	Manufacturer	Feature size/μm	Memory organization	Bias/V
R1LP0408CSP	Renesas	0.25	4 M (512 K × 8)	5.0
HM62V8100LT15	Renesas	0.18	8 M (1024 K × 8)	3.3

Both TID and SEU can be caused by protons, so there is the possibility to carry out TID exposures and SEU measurements under proton irradiation in one experiment. The TID exposures can be carried out under high flux protons to cumulate the total dose in a short time and the TID damage will

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grow up with increasing proton fluence. The SEU measurements can be carried out under low flux protons to obtain the SEU cross sections accurately.

The protons from the heavy ion accelerator laboratory of Peking University were used and the energy could be adjusted from 1 MeV to 10 MeV. According to the experiment conditions of the laboratory, the proton energy was chosen to be 3 MeV and the flux could be adjusted from 1×10^5 cm^{-2}·s^{-1} to 1×10^9 cm^{-2}·s^{-1}. Although high energy protons (energy higher than 200 MeV) cannot be accessed by us at present, the trend of the SEU sensitivity can still be reflected qualitatively and impersonal by using the 3 MeV protons and the qualitative analysis of the synergistic effect mechanism is not influenced.

The checkerboard pattern (CB, an alternating series of 0's and 1's) was applied during the TID exposure with high flux protons. Meanwhile four kinds of test patterns, checkerboard pattern, checkerboard complement pattern (CBc), and checkerboard half-complement patterns (all 0's and all 1's), were applied in the SEU sensitivity measurements with low flux protons at pre-TID-irradiation and after several different level TID radiations. In the low flux proton SEU measurements, a negligible dose was deposited in comparison with the TID exposure.

All tests were carried out using an independent online test system produced by the Northwest Institute of Nuclear Technology. The test system could achieve high speed write and read as well as real-time error detection.

3. Experimental results

The TID effects on SEU sensitivity for 0.18-μm and 0.25-μm SRAMs are illustrated in Figs. 1 and 2. The TID irradiations were performed using 1×10^9 cm^{-2}·s^{-1} protons with the CB pattern written to the memory array, and the subsequent SEU sensitivity measurements were performed using 1×10^5 cm^{-2}·s^{-1} protons with four different patterns (CB pattern, CBc pattern, all 0's, and all 1's) written to the memory array. Too much TID exposure will cause the device function invalidation and the device cannot read and write correctly. Thus before each SEU measurement, the device function must be checked to ensure that the device can read and write correctly during the following SEU measurement. The experiment will stop when the device has functional errors caused by overmuch TID exposure.

As shown in Fig. 1, with the same CB pattern during the irradiations and measurements, the SEU cross section is mainly a constant. While with the CBc pattern, the SEU cross section increases from 2.5×10^{-8} cm^2/device to 9.5×10^{-8} cm^2/device with increasing TID. In addition, with the half-complement, all 0's, and all 1's patterns, the SEU cross section increases slightly from 2.5×10^{-8} cm^2/device to about 4.0×10^{-8} cm^2/device with increasing TID.

The result in Fig. 2 is similar to the above test result. With the same CB pattern during the irradiations and measurements, the SEU cross section increases slightly from 3.5×10^{-8} cm^2/device to about 4.0×10^{-8} cm^2/device with increasing TID. While with the CBc pattern, the SEU cross section increases from 3.3×10^{-8} cm^2/device to 8×10^{-8} cm^2/device with increasing TID.

As a result, the TID effect on the SEU sensitivity depends on the device type and the test patterns during TID irradiations and SEU measurements. The SEU sensitivity increases when the test patterns complement during TID irradiations and SEU measurements, however, the SEU sensitivity mainly keeps constant when the test patterns are the same. The synergistic effect is called the imprint effect.

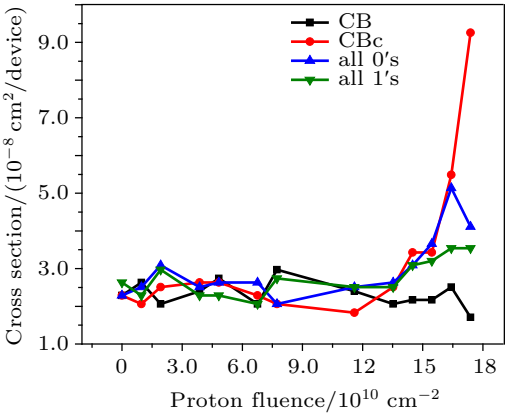


Fig. 1. (color online) Trend of 0.18-μm SRAM SEU cross section.

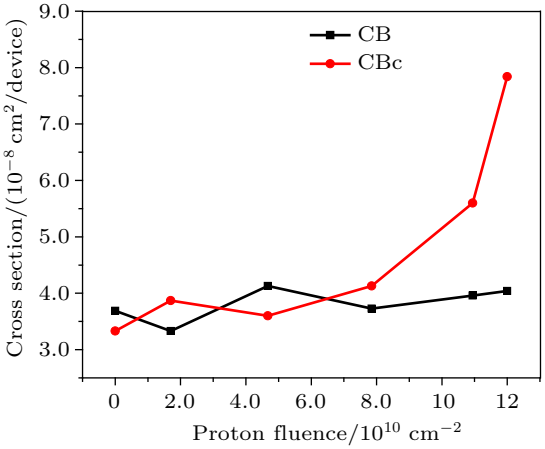


Fig. 2. (color online) Trend of 0.25-μm SRAM SEU cross section.

4. Analysis and discussion

4.1. SEU sensitive region distribution

The distribution of the SEU sensitive region in the SRAM is the premise to effect mechanism analysis. As shown in Fig. 3, the SEU sensitive region differs with the particle LET.[13] When the LET is 5 MeV·cm^2/mg, the sensitive region is in the NMOS drain and no SEU could happen in the PMOS drain.

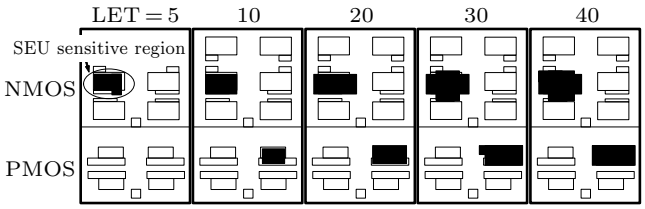


Fig. 3. Distribution of SRAM SEU sensitive region under different LET.

In the proton experiment, the SEU is induced by the Coulomb scattered protons generated from the elastic impact between 3 MeV protons and Si atoms. The LET of the Coulomb scattered protons, about 1 MeV·cm^2/mg, is less than 5 MeV·cm^2/mg, so most of low-energy-protons-induced SEU will happen in the NMOS drain and the PMOS SEU can be ignored as well. This conclusion will be used in the analysis of the imprint effect mechanism below.

4.2. Analysis of experiment result

The typical layout of a 6-T CMOS memory cell is shown in Fig. 4, and the main part is made up of four transistors of N_1 (NMOS), N_2 (NMOS), P_1 (PMOS), and P_2 (PMOS).[14,15]

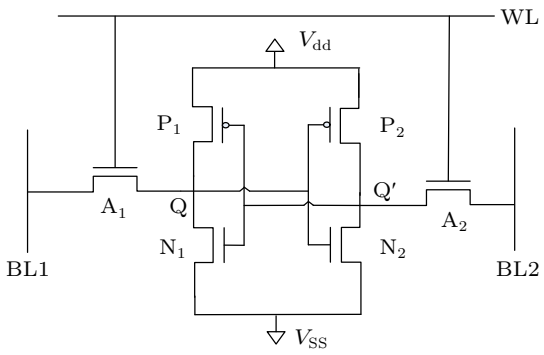


Fig. 4. The layout of a 6-T CMOS memory cell.

For the 0.18-μm and 0.25-μm devices in this study, because the gate oxide is too thin and the field oxide is thick, the trapped charge induced by the TID is mostly collected in the field oxide. The gate oxide trapped charge can cause a threshold voltage shift, while the field oxide trapped charge can cause an increase in the leakage current. So a leakage current increase is the main effect (in comparison with the threshold voltage shift) during the TID exposure.[16,17]

During the TID exposure, when $Q = 1$ is stored in the cell, P_2 and N_2 in the worst bias are most seriously damaged and the off-state leakage currents in P_2 and N_2 will increase dramatically.

If a complement pattern ($Q = 0$ and $Q' = 1$) is stored during the SEU measurement, the drain of N_2 is the main SEU sensitive region. Because of the off-state leakage current in N_2 and the parasitic resistance, the drain voltage of N_2 drops a little and is slightly below the high voltage level. When a proton strikes the N_2 drain, a negative voltage pulse will be induced by enough ionization charge and cause SEU at last. Because of the superposition of the dropped NMOS drain voltage and the negative voltage pulse, the SEU will be more likely to take place and the SEU sensitivity will increase as well. In addition, the SEU sensitivity has a direct relationship with the leakage current. More TID exposure and larger leakage current will be caused, thus the SEU sensitivity will increase due to the increasing proton fluence.

If the same pattern ($Q = 1$ and $Q' = 0$) is stored during the SEU measurement, the drain of N_1 is the SEU sensitive region. P_1 and N_1 are not in the worst bias during the TID exposure and the leakage current does not increase, so the drain voltage of N_1 will not drop. Therefore, the SEU sensitivity will not be influenced when a proton strikes the N_1 drain.

4.3. Noise margin degradation

The imprint effect can also be reflected in the noise margin degradation. The transform feature lines and the noise margins of the SRAMs are shown in Fig. 5. For the left CMOS inverter ($CMOS_1$), which consists of N_1 and P_1, the input voltage is V_1, the output voltage is V_2, and the transform feature line is line 1 in Fig. 5. For the right CMOS inverter ($CMOS_2$), which consists of N_2 and P_2, the input voltage is V_2, the output voltage is V_1, and the transform feature line is line 2 in Fig. 5. The left square in Fig. 5 is the noise margin of memory note $Q = 0$, and the right one is the noise margin of memory note $Q' = 0$.

As analyzed in subsection 4.2, when $Q = 1$ is stored in the cell during the TID exposure, P_2 and N_2 in the worst bias are most seriously damaged and the off-state leakage current increases dramatically. Thus, the TID-induced off-state leakage current will change the transformer feature line 2 and the noise margin as shown in Fig. 6.

When the SEU test pattern is opposite to the TID exposure pattern, the drain voltage of N_2 (V_1, the output voltage of $CMOS_2$) will drop a little due to the TID-induced off-state leakage current and the parasitic resistance. The drop of V_1 causes a change in the transformer feature line 2. As a result, the noise margin will decrease and the SEU sensitivity will increase.

However, when the SEU test pattern is the same as the TID exposure pattern, the drain voltage of N_1 (V_2, the output voltage of $CMOS_1$) will have no change because of the little TID damage in N_1 and P_1. As a result, the noise margin and the SEU sensitivity will mainly stay constant.

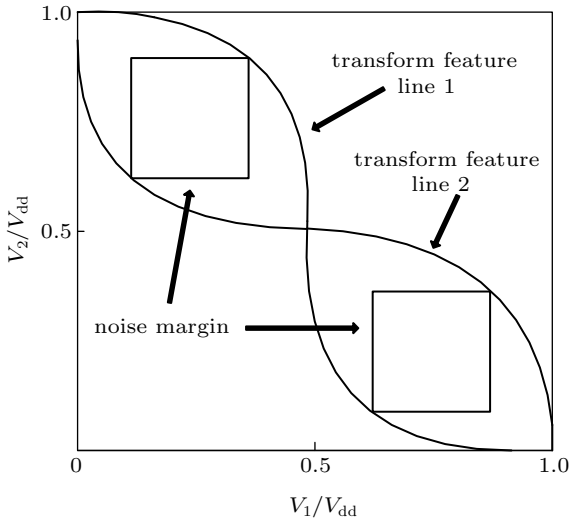


Fig. 5. Noise margin before TID exposure.

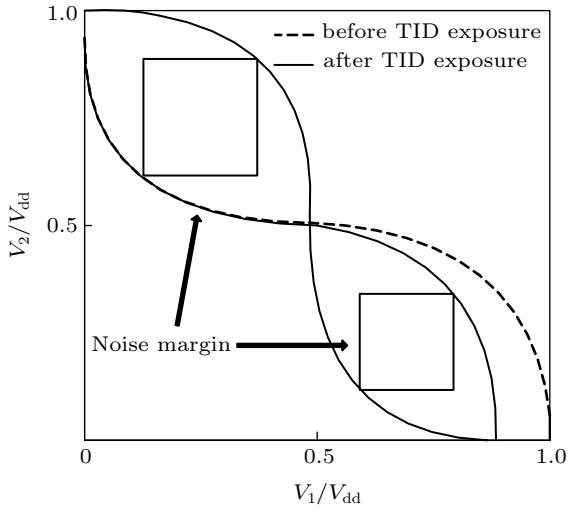


Fig. 6. Change of noise margin after TID exposure.

4.4. Displacement damage

During the TID exposure and the SEU measurements, the displacement damage (DD) may be caused by the protons and induce some defects in the semiconductor.[18] The majority carriers in the devices may be trapped by the induced defects and result in the decrease of the doping density in the semiconductor. This effect named the carrier removal effect could makes N-type and P-type materials tend to intrinsic materials.

If the induced defects could trap enough majority carriers, the absolute values of the threshold voltages of both NMOS and PMOS would change and the noise margin would degrade.

During the whole experiment, the total proton fluence is about 2.5×10^{11} cm^{-2} and is lower by 6–8 orders compared with the doping densities of N-type and P-type materials. So the displacement damage could be ignored in the final test results.

5. Conclusions

The impact of the proton-induced TID on the SEU sensitivity in 0.18-μm and 0.25-μm SRAMs has been studied. It is shown that the test patterns written to the memory array during the TID exposure and the SEU measurement greatly affect the synergistic effect of TID on SEU sensitivity. In this experiment, the imprint effect is caused by the TID-induced off-state leakage current and is obvious when the total dose is cumulated with increasing proton fluence during the TID exposure. The proton-induced displacement damage during the whole experiment could be ignored.

References

[1] Zhang K Y, Zhang F Q, Luo Y H and Guo H X 2013 *Chin. Phys. B* **22** 028501
[2] Liu F Y, Liu H Z, Liu B W, Liang B and Chen J J 2011 *Acta Phys. Sin.* **60** 046106 (in Chinese)
[3] Dodd P E, Schwank J R, Shaneyfelt M R, Ferlet-Cavrois V, Paillet P, Baggio J, Hash G L, Felix J A, Hirose K and Saito H 2007 *IEEE Trans. Nucl. Sci.* **54** 889
[4] Buchner S, Sibley M, Eaton P, Mavis D and McMorrow D 2010 *IEEE Trans. Nucl. Sci.* **57** 1805
[5] Stassinopoulos E G, Brucker G J, Gunten O V and Kim H S 1989 *IEEE Trans. Nucl. Sci.* **36** 2330
[6] He B P, Ding L L, Yao Z B, Xiao Z G, Huang S Y and Wang Z J 2011 *Acta Phys. Sin.* **60** 056105 (in Chinese)
[7] Campbell A B and Stapor W J 1984 *IEEE Trans. Nucl. Sci.* **30** 4085
[8] Matsukawa T, Kishida A, Tanii T, Koh M, Horita K, Hara K, Shigeta B, Goto M, Matsuda S, Kuboyama S and Ohdomari I 1994 *IEEE Trans. Nucl. Sci.* **41** 2071
[9] Schwank J R, Shaneyfelt M R, Felix J A, Doss P E, Baggio J, Ferlet-Cavrois V, Paillet P, Hash G L, Flores R S, Massengill L W and Blackmore E 2006 *IEEE Trans. Nucl. Sci.* **53** 1772
[10] Schwank J R, Dodd P E, Shaneyfelt M R, Felix J A, Hash G L, Ferlet-Cavrois V, Paillet P, Baggio J, Tangyunyong P and Blackmore E 2004 *IEEE Trans. Nucl. Sci.* **51** 3692
[11] Koga R, Yu P, Crawford K, George J and Zakrzewski M 2009 *IEEE Trans. Nucl. Sci.* **56** 127
[12] Xiao Y, Guo H X, Zhang F Q, Zhao W, Wang Y P, Ding L L, Fan X, Luo Y H and Zhang K Y 2014 *Acta Phys. Sin.* **63** 018501 (in Chinese)
[13] Zhang K Y, Guo H X, Luo Y H, He B P, Yao Z B, Zhang F Q and Wang Y M 2009 *Acta Phys. Sin.* **58** 8651 (in Chinese)
[14] Zhang K Y, Guo H X, Luo Y H, Fan R Y, Chen W, Lin D S, Guo G and Yan Y H 2011 *Chin. Phys. B* **20** 068501
[15] Ding L L, Guo H X, Chen W, Yan Y H, Xiao Y and Fan R Y 2013 *Acta Phys. Sin.* **62** 188502 (in Chinese)
[16] He B P, Ding L L, Yao Z B, Xiao Z G, Huang S Y and Wang Z Z 2011 *Acta Phys. Sin.* **60** 056105 (in Chinese)
[17] Liu Z L, Hu Z Y, Zhang Z X, Shao H, Ning B X, Bi D W, Chen M and Zou S C 2011 *Acta Phys. Sin.* **60** 116103 (in Chinese)
[18] Tang X X, Luo W Y, Wang C Z, He X F, Zha Y Z, Fan S, Huang X L and Wang C S 2008 *Acta Phys. Sin.* **57** 1266 (in Chinese)