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High energy proton and heavy ion induced single event transient in 65-nm CMOS technology

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As technology extends to nanometer scales, the critical charge to induce a single event decreases along with the technology node, and the threshold linear energy transfer (LET) for a soft error also decreases [1]. Meanwhile, as the operating frequency of the integrated circuit (IC) increases, the possibility for single event transients (SETs) to be captured increases. Moreover, SETs have exceeded single event upsets (SEUs) and become the dominant source of soft errors in space-used integrated circuits [2]. The distribution of SET pulse widths is the critical basis for SET mitigation [3]. Placing temporal filters at inputs of storage elements is a common way to achieve SET hardening. When the pulse width is smaller than the filter's delay, the filter output is a floating value and retains at the previous value. However, the temporal redundancy fails for long SETs. To efficiently mitigate SETs by design, it is essential to know the pulse widths of the SETs using a specific technology and explore those factors that influence the SET pulse widths.

Experiment details. A pulse width test chip is designed and fabricated with a 65-nm bulk-Si 1P7M CMOS process. The target part contains target chains of many typical logic cells where the SETs are generated under irradiation. The target chain consisting of inverters, nand gates and nor gates, named INV, NAND and NOR, respectively. To reduce the SET propagation-induced pulse broadening (PIPB), the target structure is designed as a parallel one [4]. The pulse capture part determines the temporal width of the generated SETs and the pulse capture circuit has a wide measurement range up to 1 ns and a resolution of ± 28.5 ps at 23°C.

The proton and heavy ion tests were conducted at the China Institute of Atomic Energy. The energies of protons are 70, 80, and 100 MeV. Heavy ions used in the test include Cl, Ti, and Ge. The fluence of heavy ions is 1×10^7cm^{-2}, and the fluence of protons is 2.46×10^{13} cm^{-2}.

SET cross section. The LET of a high-energy proton is too small to cause the SETs by direct ionization. Instead, high-energy protons induce the SETs by creating secondary particles through proton/material nuclear interactions. These secondary particles have much higher LET than the incident protons. The SET cross-section is defined as the detected SETs divided by the particle fluence. From Figure 1(a), the cross-section of high-energy proton induced the SETs is relatively small, from 5×10^{-12} cm^2 to about 1×10^{-11} cm^2, which confirms that the SETs induced by the protons are attributed to the secondary particles rather than the protons themselves. From Figure 1(b), we

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obtain the cross-section of the heavy ion-induced SETs are much larger, from 5×10^{-6} cm^2 to 2.2×10^{-5} cm^2. The SET cross-section under high-energy protons have little dependence on the proton energy while the cross-section increases with LET under heavy ion irradiation. This is reasonable because the SETs induced by high-energy protons are caused by secondary particles and the probability of nuclear interaction is independent of proton energy. Meanwhile, the heavy ions with higher LETs will deposit more energy and are more likely to induce a SET. Therefore, the cross-sections of the SETs induced by the heavy ions increase with the ions' LET. It is observed that the NAND chain SET cross-section is different from those of the INV and NOR. The NAND has a relatively low cross-section under high-energy proton irradiation and the cross-section of NAND increases slowly with LET under heavy ion irradiation.

SET cross-section analysis. The MOSFET in all gates are the same size, but these gates are different in structure. The parallel PMOS in the NAND gate is considered the reason that the cross-sections have distinctive features. It is known that the N-well potential is more likely to be disturbed by the particles, so the PMOS parasitic bipolar effect is more likely to be triggered by high LET particles [5]. When the PMOS is placed in parallel, the sources of two PMOSs help to collect charge and mitigate the SET pulse width as well as the SET counts. In the NOR gate, the NMOS is placed in parallel, but in this situation, the PMOS is placed in series and cannot provide enough drive current and results in wider SETs when heavy ions hit the NMOS. When heavy ions hit the PMOS, the parallel NMOS can provide a larger current; however, the disturbance of the N-well potential will trigger the parasitic bipolar effect and also results in a wide SET, which can be captured. Thus, the cross-section of the NOR is higher than that of the NAND, and grows faster with ion LET.

SET pulse width. The SET pulse width of different logic gates induced by high-energy protons can be seen in Figures 1(c)–(e) and the SET pulse width induced by the heavy ions can be seen in Figures 1(f)–(h). From Figures 1(c)–(e), the pulse widths of the proton SETs differ slightly at different proton energy. Higher-energy protons tend to create higher LET particles, but the difference in proton energy is not significant so the SET distribution looks similar at different proton energy. Furthermore, the pulse widths of the heavy ion-induced SETs have a positive relationship with ion LET, which is displayed in Figures 1(f)–(h). The maximum pulse width and the common pulse width both increase with LET. Besides, the SET pulse widths induced by the protons are equal to, or even wider than the heavy ion-induced SETs. This is obviously different from the results obtained in [6], where the pulse widths of the proton-induced SETs are shorter than the SETs produced by the heavy ions. The LET of the recoil nucleus is up to 15 MeV·cm^2/mg when the protons interact with the silicon. However, when the protons collide with a metal, such as tungsten and copper, it is possible that the recoil nucleus has a large LET [7]. It has been found in [7] that the fission fragments have a maximum LET value of 42 MeV·cm^2/mg when high-energy protons interact with tungsten. In our technology, the contact material is tungsten and the metal is copper. Thus, the pulse widths of the high-energy proton-induced SET are equal to heavy ion-induced SETs.

SET pulse width distribution. Furthermore, the distribution of the SET pulse widths in different gate cells display different features, both under proton irradiation and heavy-ion irradiation. The SET pulse width distribution of INV and NOR looks similar both under proton and heavy-ion irradiation while the NAND has a different distribution. The distribution of SET pulse widths under heavy-ion irradiation has additional characteristics which is known as a multi-peak phenomenon and is analyzed in [3]. The multi-peak phenomenon under heavy-ion irradiation is believed bo be attributed to the PMOS parasitic bipolar effect being triggered by high LET heavy ions. However, the high-energy proton SET distribution does not have a multi-peak. The difference between heavy ion and high-energy proton irradiation reveals the distribution of SET pulse widths depends on both device structure and radiation. It is observed that the heavy ion LETs remain unchanged in the experiment while the recoil nucleus induced by the protons has different LETs, where high LET recoils only account for a very small proportion. As a result, wide SETs caused by high LET recoils are relatively small in number and the distribution of SET pulse widths has no multi-peak.

Conclusion. The SETs of INV, NAND and NOR gates with 65-nm CMOS technology are measured under high-energy protons and heavy ions. The SET cross-section and the SET pulse width distribution are measured and analyzed. The NAND cross-section displays a different trend compared with the other two logic gates, which is believed to be due to the parallel PMOS. The SET pulse widths under high-energy protons and heavy ions are compared and analyzed to determine the influence of irradiation conditions and device structures on the SET pulse width. The pulse width of the SETs induced by protons is equal to or even larger than the SETs induced by heavy

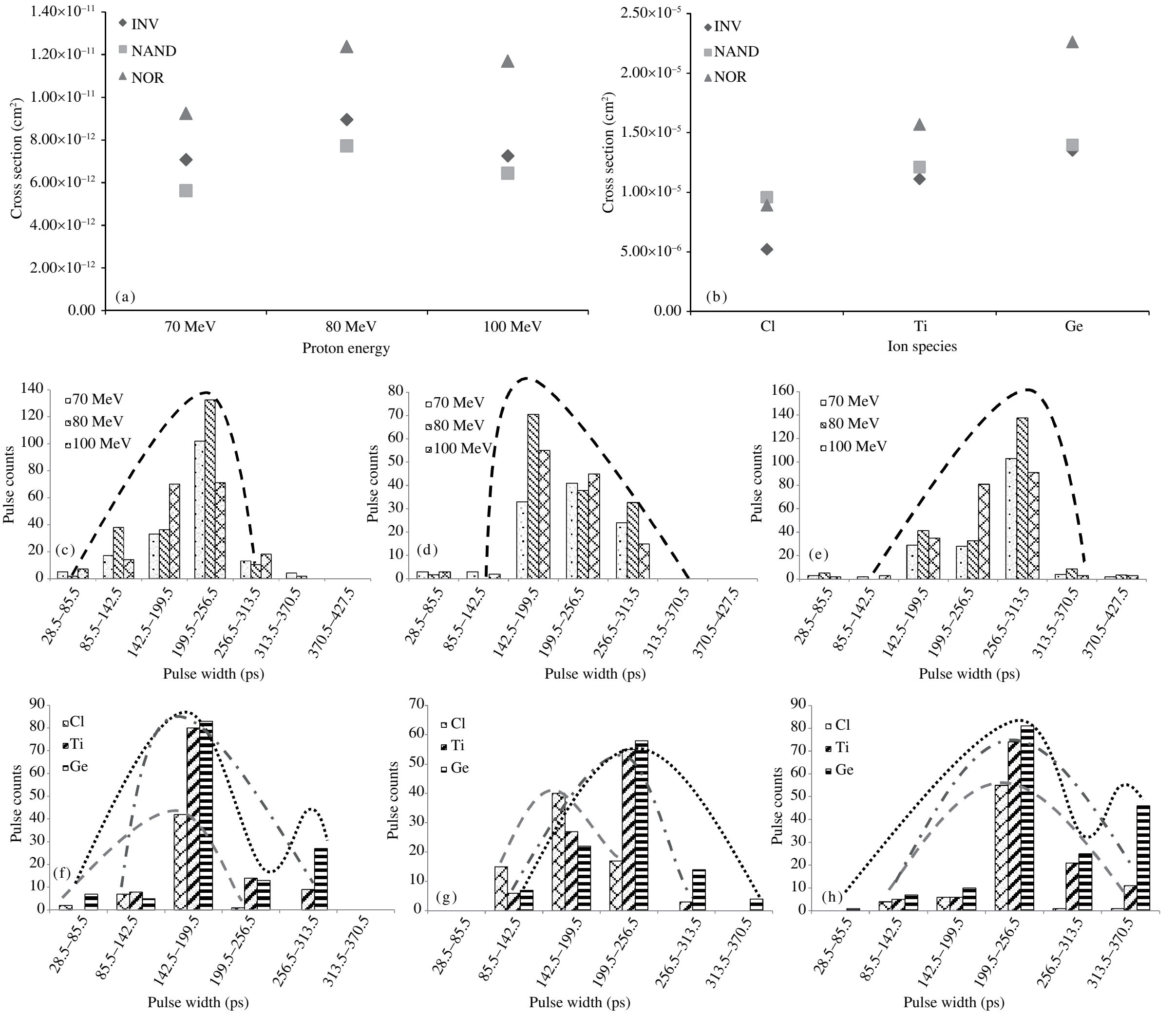

Figure 1 The SET experiment and experimental results. The SET cross-section under (a) high-energy protons and (b) heavy ions; the (c) INV, (d) NAND, and (e) NOR SET pulse width distribution under high-energy protons; the (f) INV, (g) NAND, and (h) NOR SET pulse width distribution under heavy ions.

ions. The likely reason is the nuclear interaction of the proton with tungsten and then the creation of high LET secondary particles. The SET pulse width distribution under protons and heavy ions looks similar except the dual peak observed in the heavy ion SET. The NAND SETs distribution has a different trend compared with those of the INV and NOR, both under high-energy protons and heavy ions, which is also attributed to the parallel PMOS in the NAND.

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