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The Effect of Energy Loss Straggling on SEUs Induced by Low-Energy Protons in 28 nm FDSOI SRAMs

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Abstract: Sensitive volume thickness for silicon on insulator (SOI) devices has scaled to the point that energy loss straggling cannot be ignored within the development of the manufacturing process. In this study, irradiation experiments and Geant4 simulation were carried out to explore the influence of energy loss straggling on single event upsets (SEUs) caused by sub-8 MeV proton direct ionization. We took a 28 nm fully-depleted SOI static random-access memory (SRAM) as the research target. According to our results, the depositing energy spectrum formed by monoenergetic low-energy protons that penetrated through the sensitive volume of the target SRAM was extremely broadened. We concluded that the SEUs we observed in this article were attributed to energy loss straggling. Therefore, it is sensible to take the new mechanism into consideration when predicting proton-induced SEUs for modern nanometer SOI circuits, instead of the traditional linear energy transfer (LET) method.

Keywords: energy loss straggling; low-energy proton; single event upset; sensitive volume; fully-depleted silicon on insulator; linear energy transfer

1. Introduction

As an important type of space application integrated circuits, SRAM has attracted much attention about improving its irradiation resistance, in which single event upsets (SEUs) are the main issue referring to a storage state changed by one single ionizing particle striking a sensitive node. Silicon on insulator (SOI) technologies can effectively suppress short channel effect and have intrinsic hardness towards single event effects (SEEs) [1,2], therefore it may be a preferable choice compared with bulk technologies for sub-28 nm process nodes.

Space is a proton rich environment [3] and proton-induced SEU and were conventionally dominated by secondary ions generated from nuclear reactions between high-energy protons and other atoms in devices [4]. However, SRAMs have scaled to the point that even protons with low-energy can deposit sufficient energy in the sensitive volume to cause upsets via direct ionization [5]. For example, it was reported that the low-energy proton cross-section was more than 1000 times larger at 0.65 MeV than at 200 MeV for 90 nm bulk SRAMs [6]. Meanwhile, the feature size of integrated circuits further shrinking may bring a new challenge. Previous studies reported that energy deposited in thin silicon layers by light ions such as protons should be treated as a broadened energy spectrum instead of one single value [7,8]. The phenomenon is known as energy loss straggling, contradicting the accuracy of soft error rates evaluation method based on LET. SOI devices have much smaller sensitive volume than bulk ones. For instance, the body region and the active region of a transistor manufactured with ST28 ultra-thin buried oxide and body fully depleted SOI (UTBB FDSOI) technology are merely 7 nm and 22 nm thick [9], respectively. This means that energy loss straggling should not be ignored any more in the future.

Prior researchers have contributed to the issue. For example, a 22 nm SOI SRAM cell in Geant4 was established to explore the influence of energy loss straggling on high-energy proton-induced SEUs through direct ionization [10]. By contrast, direct ionization is the dominant mechanism of low-energy proton-induced upsets, as mentioned above. It may be more valuable to study the impact of energy loss straggling on SEUs when SRAMs are irradiated by low-energy protons.

The present article performed irradiation experiments by using a SRAM fabricated with the ST28 FDSOI technology with sub-8 MeV protons and constructed a corresponding memory cell model in Geant4 to calculate deposited energy in the sensitive volume. Section 2 gives details about the method of experiments and Geant4 simulation. According to results presented in Section 3, the SEUs caused by proton direct ionization can be ascribed to energy loss straggling. Finally, Section 4 makes a thorough discussion about the reason that energy loss straggling cannot be ignored for modern SOI circuits and provides some advice of SEU evaluation methods.

2. Methods

2.1. Experimental Method

A commercial 160 kb SRAM fabricated with the ST28 FDSOI CMOS technology was irradiated by protons in 2–8 MeV energy range using the EN tandem accelerator in Peking University (PKU). It consisted of classical six-transistors bit-cells, as shown in Figure 1.

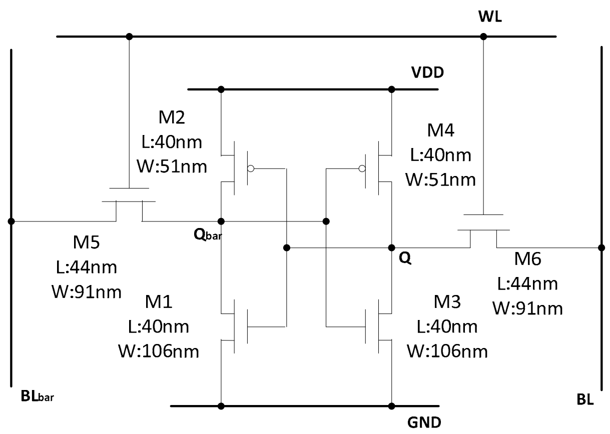


Figure 1. A bit-cell in the ST28 FDSOI SRAM with detailed size of transistors.

The SRAM under test was initialized with a checkerboard pattern beforehand. During its exposure to protons, a connected field-programmable gate array (FPGA) read data that was stored in all memory cells periodically. The FPGA recorded upsets once upsets were generated and then wrote correct data to the error bits. After that, a new read cycle started. Furthermore, real-time error message could be received by the monitor computer. To guarantee that protons arrived at the surface of devices were monoenergetic, no degrader was used; all tests were conducted in vacuum. Proton energy was regulated by changing the high voltage of the Van de Graaf generator when using the EN tandem accelerator and it had desirable accuracy (error within ± 2%). Table 1 gives details about experimental setup in this study.

Table 1. Experimental Setup.

Proton Energy [MeV]	Incident Direction	Proton Fluence [ions/cm^2]
2	Vertical	6.38×10^{11}
3	Vertical	3.93×10^{11}
5	Vertical	2.93×10^{11}
8	Vertical	3.25×10^{12}

To avoid the harmful influence of total ionizing dose (TID) effects on SEU results [11], a SRAM circuit was only tested by one single energy point. Operating voltages and currents of irradiated circuits were carefully monitored because electrical characteristics can effectively reflect the device degradation resulted from TID. Irradiation was terminated as long as significant changes were observed for electrical characteristics. Though TID effects may not have been ruled out thoroughly, it has been minimized in the present experiment.

2.2. Geant4 Simulation Setup

The Geant4 simulation was carried out to estimate the importance of energy loss straggling for SEUs induced by low-energy proton direct ionization.

Firstly, a relevant six-transistor memory cell model was constructed. Inspection of Figure 2 indicates a ST28 FDSOI transistor, in which the body depth is merely 7 nm and the raised active region is only 22 nm thick. In this paper, the drain region is treated as sensitive volume due to its considerably higher sensitivity than the body region according to our earlier research [12]. For reasonably estimating the distribution of energy deposited in sensitive volume, it is necessary to consider the impact of back-end-of-the line (BEOL) [13]. We adopted identical method with the IBM SEU simulation model named SEMM-2 [14] by abstracting BEOL as a number of layers, each of which can be either metal material or dielectric material. As information about the manufacturing process of ST28 FDSOI technology was limited, we adopted a moderate method that BEOL parameters were obtained from the process design kit (PDK) of a 28 nm bulk technology belonging to United Microelectronics Corporation (UMC) and metal stacks were modified according to the data presented by the PDK of ST28 FDSOI technology. Though the BEOL model was a little different from its actual situation, it was negligible because variations in the BEOL do not have apparent influence on the average energy deposited in a sensitive volume by direct ionization [15]. Figure 3a illustrates a top view of the memory cell model carefully constructed in Geant4. The model was 1600 nm long and 1200 nm wide. Diagonal-distributed rectangles and vertical line-distributed rectangles in Figure 3a represented the drain region and the source region, respectively, while dotted rectangles were regarded as the body. Figure 3b shows a cross-sectional schematic diagram of the model. There were ten copper stacks including six thin layers, two intermediate layers and two thick layers, whose thickness were 0.1 µm, 0.2 µm and 0.8 µm, respectively.

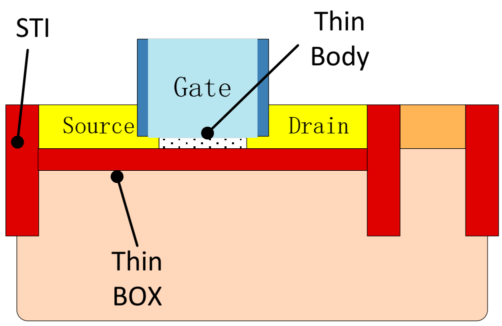
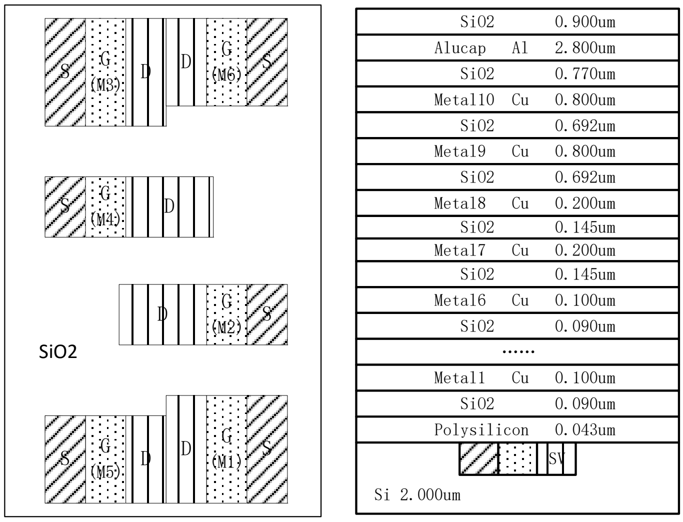


Figure 2. A ST28 ultra-thin buried oxide and body fully depleted silicon on insulator (SOI) transistor.

The Geant4 simulation was conducted for normal incidence with five million protons randomly striking the surface of the model at each energy point. The equivalent proton fluence was 2.60×10^{14} ions/cm^2. Detailed information about the simulation setup is given in Table 2.



(**a**) (**b**)

Figure 3. (**a**) The top view of the memory cell model established in Geant4; (**b**) The front view of the Geant4 model.

Table 2. Simulation Setup.

Proton Energy [MeV]	Incident Direction	Proton Number
0.90	Vertical	5×10^6
0.92	Vertical	5×10^6
2	Vertical	5×10^6
3	Vertical	5×10^6
5	Vertical	5×10^6
8	Vertical	5×10^6

3. Results

Under the circumstance of energy loss straggling being ignored, SEUs should not have been observed during exposure. The possibility of nuclear reactions between low-energy protons and other atoms in devices is extremely low, therefore upsetting observed in experiments were actually caused by proton direct ionization. According to the method based on LET, energy deposited in sensitive volume referred to the 22 nm thick drain region can be calculated by (1) and the results are presented in Table 3. In Formula (1), P_{LET} and ΔX represent the LET of proton in silicon and the trajectory length of an incident particle, respectively, whereas ρ_{Si} is the density of silicon. It is worth noting that protons with different energy correspond to different LET values according to SRIM calculation.

$$\mathrm{E} = P_{LET} \times \Delta X \times \rho_{Si} \tag{1}$$

The minimum depositing energy E_{depo_min} required to trigger SEUs could also be calculated by (1), which was 4.60 keV. It was considerably larger than the results shown in Table 3. The supply voltage of SRAMs was observed to modestly descend to 0.8 V on account of TID effects during performing experiments. And a relevant prediction of 0.9 MeV-cm^2/mg for the threshold LET was made by technology computer aided design (TCAD) simulation. Thus, the value P_{LET} should be 0.9 MeV-cm^2/mg here.

Table 3. Energy deposited in the sensitive volume calculated with LET method.

Proton Energy [MeV]	LET in Silicon [MeV-cm^2/mg]	Energy Deposited [eV]
2	0.1124	573.99
3	0.0849	433.55
5	0.0587	299.76
8	0.0413	210.90

However, SEUs induced by protons with initial energy ranging from 2 MeV to 8 MeV indeed existed, as showed in Table 4. The cross-sections of each energy point were calculated by (3) and relevant results were given in Figure 4. In Formula (3), N_{upsets} represents the number of upsets recorded by the monitor computer while F_{proton} and V_{SRAM} represent particle fluence and memory capacity, respectively. Since multiple-bit upsets (MBUs) were hardly observed during exposure, black circles are virtually regarded as single-bit upsets (SBUs).

$$\text{Cross} - \text{Section} = \frac{N_{upsets}}{F_{proton} \times V_{SRAM}} \tag{2}$$

Table 4. Experimental SEU results.

Proton Energy [MeV]	Upsets	Cross-Section [cm^2/bit]
2	7	6.70×10^{-17}
3	9	1.40×10^{-16}
5	6	1.25×10^{-16}
8	44	8.26×10^{-17}

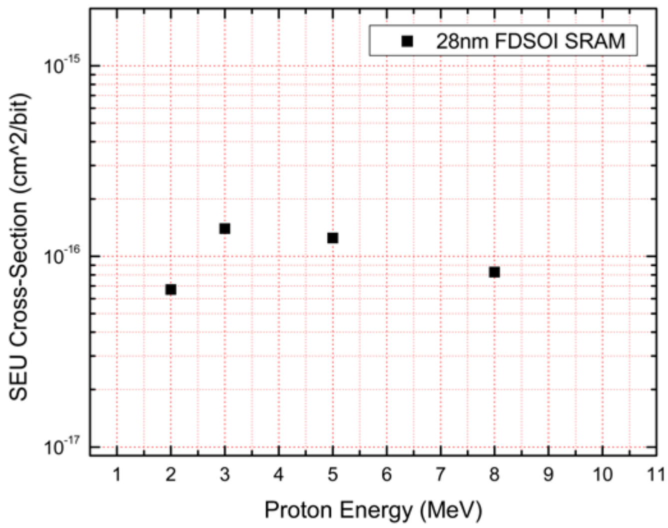


Figure 4. SEU cross-sections at each energy point.

There is a variation of energy collection efficiency in different regions of the sensitive volume [3]. Consequently, this factor should be taken into consideration to more accurately evaluate SEU cross-sections. The sensitive volume was divided into three parts according to [3], as shown in Figure 5. Part 1 and part 3 corresponded to quite low energy collection efficiency of 10% which could be ignored, whereas part 2 occupying about half of the area corresponded to a high value. The value was calculated by (3). In this equation, E_{depo_min} and E_{colle_min} represent the minimum depositing energy of 4.60 keV and the critical energy of 3.82 keV, respectively. The critical energy was expressed by (4), in which Q_e is the elementary charge and ε is the average energy of 3.6 eV demanded to generate an ionized electron-hole pair in silicon, while $Q_{critical}$ is the equivalent critical charge to E_{colle_min} In order to precisely evaluate the critical charge, a six-transistor memory cell model was established and calibrated according to the ST28 FDSOI PDK in TACD. Ions with threshold LET struck the drain region of an off-state inverter NMOS. The critical charge was estimated to be 0.17fC by integrating the current flowing through the drain electrode. The energy deposited by a proton arriving at part 2 should be calibrated with the energy collection efficiency δ to judge whether it can trigger a SEU or not.

$$\delta = \frac{E_{colle\_min}}{E_{depo\_min}} \tag{3}$$

$$E_{colle\_min} = \frac{Q_{critical}}{Q_e} \times \varepsilon \tag{4}$$

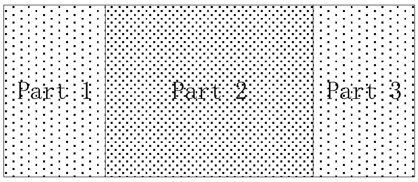


Figure 5. The divided sensitive volume.

Figure 6 illustrates results obtained from Geant4. The cumulative events number is the statistics of protons that deposited a given energy or greater in the sensitive volume. Incredibly, the energy deposited was broadened to about 10 keV, far beyond the estimated value based on LET, which will be exhaustively explained in the following paper. Protons at 0.9 MeV and 0.92 MeV tended to loss more energy in silicon, ascribing to that the Bragg peak reached the sensitive volume. This sharp peak below 1 MeV confirmed the experimental results documented by [5,16,17]. E_{depo_min} is also presented in Figure 6 as a vertical dashed line and Table 5 shows corresponding SEU cross-sections for each energy point.

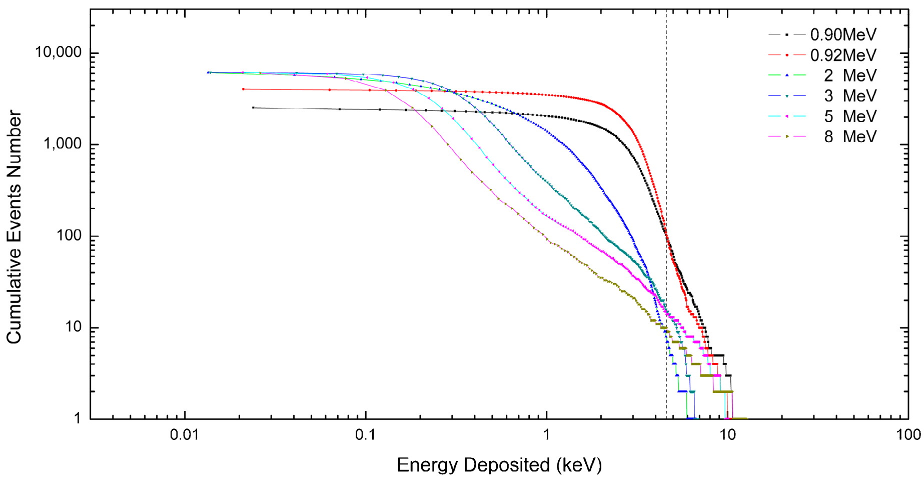


Figure 6. Geant4 simulation results. The cumulative number of protons that deposited a given energy or greater in the sensitive volume for various initial energy of the proton beam.

Table 5. Simulation results of single event upset (SEU) cross-sections.

Proton Energy [MeV]	Upsets	Cross-Section [cm^2/bit]
0.9	95	3.65×10^{-13}
0.92	100	3.85×10^{-13}
2	7	2.69×10^{-14}
3	15	5.77×10^{-14}
5	14	5.38×10^{-14}
8	10	3.85×10^{-14}

It seems that the simulation results in Table 5 were higher than these experimental results illustrated by Table 4. Some reasons may be attributable to the difference. When a proton penetrates through the sensitive volume, excited electrons along its track may diffuse to other insensitive areas before they are collected [18]. However, they were included in our simulation. The phenomenon is especially apparent for protons that arrive at the edge of the sensitive volume. On the other hand, simulation tools of Geant4 and TCAD used in this manuscript cannot fit each other perfectly at the present stage. They both have limitations when being used to research charge generation and collection for modern SOI devices. Consequently, further work should concentrate on organically combining the two simulation tools. The distinction between simulation results and experimental results is not critical, because the main aim of this article is to point out that energy loss straggling should not be ignored any more when predicting SEUs induced by protons for circuits manufactured with SOI technology, instead of proposing an evaluation method of calculating soft error rates.

Generally speaking, summarizing these results described above, it is reasonable to conclude that SEUs induced by low-energy proton direct ionization in the irradiation experiments are ascribed to energy loss straggling.

4. Discussion

Last section illustrated that energy loss straggling contributed significantly to the SEUs observed during exposure. To make further interpretation, an auxiliary experiment was performed in Geant4. Two silicon detectors were established, of which one was 1 μm thick according to the charge collection depth for nanometer CMOS bulk technologies [19] and the other was 22 nm thick corresponding to the sensitive volume of ST28 FDSOI technology. Further, 10,000 monoenergetic protons at 1.5 MeV struck each silicon detector vertically. The statistical results of deposited energy are illustrated by Figure 7, in which the frequency represents the possibility of energy lost by a proton falling into a given interval. Compared with a symmetrical less broadened energy spectrum for the 1 μm thick detector, an extremely broadened curve was obtained for the 22 nm thick one. Our results were consisted with the discovery made by previous researchers that energy loss distribution for charged particles in thin matter was similar with the Landau distribution [20]. It is worth noting that there should have been a peak in the curve presented by Figure 7b, but the peak was extraordinary narrow that it actually fell into a given energy interval.

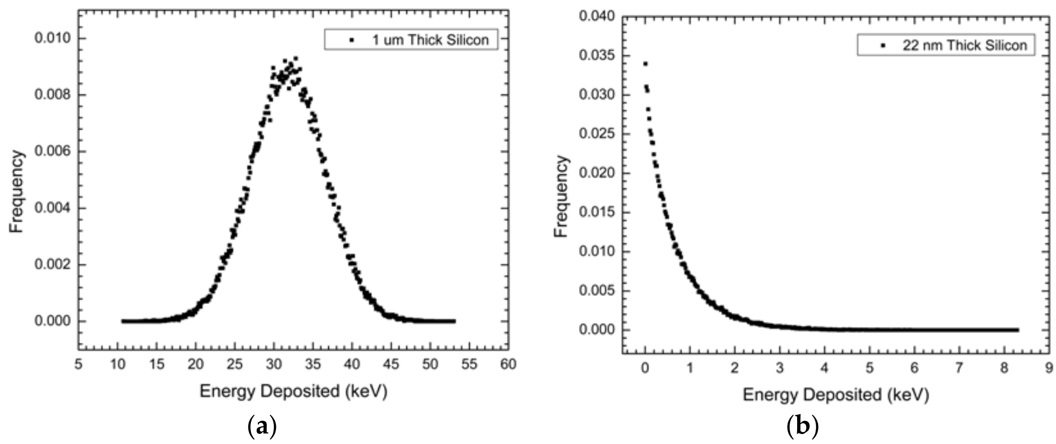


Figure 7. (**a**) Energy loss spectrum for ten thousand protons penetrating through the 1 µm thick silicon detector; (**b**) Energy loss spectrum for ten thousand protons penetrating through the 22 nm thick silicon detector.

This phenomenon can be explained by the statistical fluctuation referring to the number of collision events between protons and extranuclear electrons of silicon. As shown in Figure 8, a proton with normal incidence changes its state in terms of energy and velocity when encountering an electron. However, the final state of this proton has significant uncertainty as electrons with different kinetic energy disorderly distribute in silicon. Therefore, the distance between two collision events presents a certain randomness. This is immaterial under the circumstance of thick matter being used because a long path length for ionized particles guarantees enough collision events and energy deposited can be expressed by a mean value. By contrast, the randomness in distance means that an incident proton randomly deposits energy in ultra-thin sensitive volume, conducting in a largely broadened energy loss spectrum.

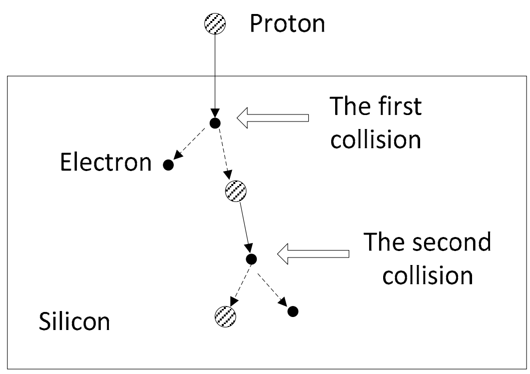


Figure 8. The schematic diagram of collisions between protons and extranuclear electrons of silicon.

Conventionally, the threshold LET is an important indicator to measure the performance of circuits which adopt radiation hardened by design (RHBD) techniques. This is based on the presumption that energy lost by monoenergetic particles in traversed material is essentially identical. But according to our Geant4 simulation, energy loss straggling is so apparent that it is unreasonable to choose a mean value to represent the ionization energy loss of protons for the 28 nm FDSOI SRAM. In other words, a proton may deposit enough energy in silicon due to energy loss straggling, although its LET calculated by SRIM is quite low. The threshold LET may not be a reliable indicator to judge whether SEUs can be triggered by given particles or not anymore.

Thus, we speculate that the previous presumption can cause an underestimation in terms of the influence of low-energy protons on SEUs for modern SOI devices. This speculation is also proved by our experiments. For instance, the actually supply voltage of SRAMs modestly descended to 0.8 V due to TID effects during performing experiments. A relevant threshold LET was estimated to be 0.9 MeV-cm^2/mg through TCAD simulation. The estimated value was considerably large than the biggest LET of proton in silicon, which is 0.54 MeV-cm^2/mg. Conversely, SEUs caused by low-energy protons indeed appeared at each energy point.

In the future, it is advised that energy loss straggling should be taken into consideration to evaluate the influence of protons on SEUs. After all, space is a proton rich environment and a more conservative evaluation merely based on LET can bring about serious consequences.

5. Conclusions

In this paper, a 28 nm FDSOI SRAM =performed irradiation experiments by using low-energy protons. Further, a relevant six-transistor model was established in Geant4 to study the feature of depositing energy spectrum in the sensitive volume. It is found that energy lost in thin traversed silicon by monoenergetic incident particles appeared a huge difference. Since the minimum energy required to trigger SEUs significantly exceeded the energy calculated based on LET method, we conclude that those SEUs induced by direct ionization are actually attributed to energy loss straggling. The new mechanism should be considered to accurately evaluate the influence of protons on soft error rates for modern SOI circuits, whereas the traditional LET based method may unavoidably result in an underestimation.

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