

Article

Investigate the Equivalence of Neutrons and Protons in Single Event Effects Testing: A Geant4 Study

Yueh Chiang ^{1,2}, Cher Ming Tan ^{3,4,5,6,*}, Tsi-Chian Chao ^{1,7}, Chung-Chi Lee ^{1,7} and Chuan-Jong Tung ⁷

- ¹ Department of Medical Imaging and Radiological Sciences, College of Medicine, Chang Gung University, Tao-Yuan 333, Taiwan; D0503203@cgu.edu.tw (Y.C.); chaot@mail.cgu.edu.tw (T.-C.C.); cclee@mail.cgu.edu.tw (C.-C.L.)
- ² Department of Radiation Oncology, Chang Gung Memorial Hospital, Tao-Yuan 333, Taiwan
- ³ Center for Reliability Sciences and Technologies, Chang Gung University, Tao-Yuan 333, Taiwan
- ⁴ Urology Department, Chang Gung Memorial Hospital, Tao-Yuan 333, Taiwan
- ⁵ Center for reliability engineering, Ming Chi University of Technology, New Taipei City 243, Taiwan
- ⁶ Department of electronic engineering, College of Engineering, Chang Gung University, Tao-Yuan 333, Taiwan
- ⁷ Particle Physics and Beam Delivery Core Laboratory, Institute for Radiological Research, Chang Gung University/Chang Gung Memorial Hospital, Tao-Yuan 333, Taiwan; cjtung@mail.cgu.edu.tw
- * Correspondence: cmtan@cgu.edu.tw

Received: 15 March 2020; Accepted: 2 May 2020; Published: 6 May 2020



Abstract: Neutron radiation on advanced integrated circuits (ICs) is becoming important for their reliable operation. However, a neutron test on ICs is expensive and time-consuming. In this work, we employ Monte Carlo simulation to examine if a proton test can replace or even accelerate the neutron test, and we found that 200 MeV protons are the closest to resembling neutron radiation with five main differences. This 200 MeV concur with the suggestion from National Aeronautics and Space Administration (NASA, Washington, DC, USA). However, the impacts of the five differences on single event effects (SEEs) require future work for examination.

Keywords: single event effects; linear energy transfer; Monte Carlo simulation; radiation hardness

1. Introduction

Technological developments bring smaller and faster devices in integrated circuits that operate at reduced bias voltages. However, they also suffer from increased susceptibility to neutrons. These neutrons can cause single event effects (SEEs) on the integrated circuits, rendering their temporary loss of function. Such temporary loss of function may be a critical issue in many applications, especially for implanted medical electronics such as pacemakers [1].

Consequently, radiation tests are becoming necessary to ensure reliable applications of these circuits, especially in applications where their exposure to radiation intensity might be higher. An example of radiation test can be found in Intel. Seifert et al. reported their radiation test results in Intel, demonstrating that radiation-induced soft error rate (SER) improvements in the 14 nm generation high-k+ metal gate as compared to the bulk tri-gate technology [2]. Its taller and narrower structure minimized the charge collection owing to a smaller, sensitive volume. There are many more reported radiations tests as can be seen in the annual workshop on soft error Silicon Errors in Logic—System Effects (SELSE). The SELSE workshop provides a forum for discussion of current research and practice in system-level error management. Participants from industry and academia explore both current technologies and future research directions (including nanotechnology). SELSE is soliciting papers that address the system-level effects of errors from a variety of perspectives: architectural, logical,



circuit-level, and semiconductor processes where several companies are reporting their radiation tests in the workshop.

However, a fast neutron test that resembles normal operating conditions is expensive due to the long test duration, and the test can only be done in limited facilities such as TRIUMF (Vancouver, BC, Canada; up to 400 MeV neutrons), Los Alamos Neutron Science Center (LANSCE, Los Alamos, NM, USA; up to 750 MeV neutrons), and ISIS Neutron and Muon Source (Oxford, UK; up to 400 MeV neutrons). Proton facilities, however, are easier to access worldwide. Another advantage of using protons to replace neutrons for SEE testing is that the protons are charged particles which can be easily accelerated and focused. Wei et al. showed the possibility and challenge of using a medical proton facility to do SEE testing [3]. In fact, the use of protons to study the radiation effect on electronics in various radiation environments has been practiced. O'Neill et al. proposed that 200 MeV proton can be used to mimic the radiation environment at low Earth orbit (LEO) [4], and National Aeronautics and Space Administration (NASA) used 200 MeV proton to perform their SEE tests, and successfully screened thousands of electronic parts at Indiana University Cyclotron Facility (IUCF, Bloomington, IN, USA) even though the previously reported SEE failures were due to heavy ions [4].

The SER in integrated circuit can be estimated by dose (or energy deposited) convoluted with energy-specific linear energy transfer (LET) [5]. In a radiation hardness test, the dose can be controllable by flux, but the LET is the characteristic of particles with specific energy. LET expresses the characteristics of a particle's path through materials. It is defined as the energy being transferred to a material by an ionizing particle as a function of distance and material density, in units of MeV-cm²/mg. Dodd et al. showed that LET is the key index of SER in high-speed digital logic integrated circuits (ICs) [6]. Bagatin et al. also showed the correlation of LET and single event upset (SEU) in floating gate cells [7]. In addition to LET, the specific secondary particles can also be important because it can create different kinds of defect in the materials in integrated circuits [3].

In this work, we examine the possible use of a medical proton test facility to replace the fast neutron test at sea level using the Monte Carlo simulation known as Geant4. To evaluate the equivalence of neutron and proton SEE tests, LET of both primary and secondary particles and secondary particle yields are examined. The secondary particle yields are also important in SEE evaluation because the secondary particles, especially for heavy ions, may implant in the silicon crystal and change the electronic properties.

Subsequent quantitative verification will be performed using our newly constructed proton center at Chang Gung Memorial Hospital (Linkou District, New Taipei, Taiwan) which is a medical cyclotron (Sumitomo Heavy Industry, Tokyo, Japan) with a maximum beam current around 300 nA at 230 MeV. The energy spread is less than 10% for low energy (30 MeV) and 1% for higher energy (110 + MeV).

2. Materials and Methods

In this work, we focus on silicon-based semiconductors. However, there are always back-end interconnected structures that contain metals with high Z materials, such as copper and refractory metals. As the spallation cross-sections of neutrons and protons are correlated to Z, the high LET secondary particles are mostly generated in the back-end structures after neutron and proton radiation, and these particles can hit the semiconductor region producing SEEs.

Another common silicon-based semiconductor material is silicon-germanium (SiGe). SiGe is an upcoming advanced silicon-based IC technology as SiGe technology effectively merges the desirable attributes of conventional silicon-based CMOS manufacturing (high integration levels, at high yield and low cost) with the extreme levels of transistor performance attainable in classical III–V heterojunction bipolar transistors (HBTs) through bandgap engineering. This renders SiGe HBTs with several key merits with respect to operation across a wide variety of so-called "extreme environments", potentially with little or no process modification, ultimately providing compelling advantages at the circuit and system level, and across a wide class of envisioned commercial and defense applications. Thus, both silicon and SiGe materials are studied in this work.

Since back-end interconnected structures are the major sources of high LET secondary particles that can induce SEEs, we need to confirm the hypothesis that the spectra of secondary particles generated from the back-end structures by protons are similar to those from the fast neutrons in the LANSCE, as shown in Figure 1 [8]. We performed this hypothesis testing using Geant4 Monte Carlo simulations [9].



Figure 1. The Los Alamos Neutron Science Center (LANSCE) broad band neutron spectrum used in this study [8].

Geant4 is a well benchmarked general-purpose Monte Carlo code for both macroscopic and microelectronic scales. Intel has used Geant4 to build their "Intel Radiation Tool" for radiation effect simulation [10]. Weller et al. also established a Monte Carlo approach for estimating SEEs using Geant4 with TCAD [11].

2.1. Monte Carlo Simulation

To simulate the LETs and secondary particle yields in semiconductor devices, Geant4 10.04.p02 was used in this work [12]. The physics list used in this study is QGSP_BIC_HP_EM4 with radioactive decay enabled. In particular, G4EmStandardPhysics_option4 was implemented for modeling Electromagnetic process, G4HadronElasticPhysics for elastic process of hadrons, G4HadronPhysicsQGSP_BIC for inelastic process of hadrons, G4RadioactiveDecayPhysics for radioactive decay, and G4IonBinaryCascadePhysics for inelastic process. The quark-gluon string precompound (QGSP) model was implemented to handle collision of high-energy hadrons, and the binary cascade model was used for inelastic process of hadrons. The high precision data were set for the low-energy neutron and light ions. The details of the hadron interaction and ionization model in Geant4 can be found in Truscott et al. [13].

Since elastic and inelastic interactions due to the nuclear reactions of radiation particles and materials are critical to predict secondary particle yields, the Joint Evaluated Fission and Fusion File (JEFF) 3.3 Nuclear Data Library was added to the neutron simulation, and the G4TENDL data set was also added for high precision particle transportation.

To obtain more accurate secondary yields, the nuclear decay model was enabled with the function DO_NOT_ADJUST_FINAL_STATE. This is a function in Geant4 which instructs the simulation software not to generate artificial gamma rays for the purpose of satisfying the energy and momentum conservation in some nuclear reactions. The simulation will follow the ENDF-6 libraries [14]. Moreover, the cut-off range for secondary particles was set to 0.01 nm, so that all the secondary particles can continuously slow down to an approximation range longer than 0.01 nm [15].

The studied primary incident particles are the LANSCE broad band neutron and protons with selected energies. These particles were generated using the Geant4 general particle source (GPS). For

4 of 14

neutrons, a spectrum from LANSCE was converted to a probability distribution (Figure 1) and inputted to the GPS. For protons, eight monoenergetic protons of 10, 30, 50, 63, 105, 150, 200, and 230 MeV respectively were generated, and only one of the above energies was simulated at a time. In each simulation case, the number of histories was 10⁹. History in the context of Monte Carlo simulation refers to a record of a primary particle from being generated to being stopped.

All the primary particles were generated on the top of the structure and transported by the Geant4 process class with the physics list mentioned above. The secondary particle species generated due to the interactions between the primary particles and materials was recorded by the Geant4 stepping class when the particles entered the detection layer. To prevent the partial volume effect, which usually happens when the scoring volume overlaps two or more materials at the geometry boundary [16], the energy deposition was calculated by the Geant4 tracking class which sums up all the energy deposition in each step from the track passing through the detection layer. The details of the Monte Carlo technique used in this work and the associated issues can be found in a study by Chiang and colleagues [17].

Since there is no method to measure the LET spectrum in an actual integrated circuit, our simulation is benchmarked with the simulation results of O'Neill for pure silicon [16], and good agreement was obtained. In fact, the same simulation setup has been used for simulating the microdosimetry property of protons and photons in biological targets with 1 μ m diameter and again good agreement was obtained. This work was reported by Hsing et al. [18].

2.2. Material Structure

The material examined in this work is a back-end structure modified from Zhang et al. [12]. The aluminum layer is replaced by copper and the detection layer is 100 nm thick, as shown in Figure 2a. No titanium layer is included in the simulation of this work. Figure 2b shows the same structure but with an additional thin SiGe layer to evaluate the effect of SiGe on SEE events due to neutron and proton radiation. Other metallization structures will be examined in our other work.



Figure 2. The layer structure (a) without SiGe and (b) with SiGe used in this simulation (not to scale).

To achieve a charged-particle equilibrium (CPE) and maintain simulation efficiency, the diameter of the structure is set to 1 mm, which is much larger than the secondary particle range. Monte Carlo simulation may have boundary crossing problems when particles transport from a large volume to a small volume. To minimize this effect, the step size in this study is limited by a stepping function that each step cannot be longer than 0.01% of its calculated range. The final step cannot be bigger than 0.1 nm. In addition, the skin parameter in this study is set to three, which means that single scattering mode will activate three elastic mean free paths before the boundary.

2.3. Data Analysis

LET is calculated from the energy deposited in the detection layer divided by its thickness (100 nm) and the density of silicon (2330 mg/cm³). The energy deposited is calculated by the sum of the energy imparted by all the events from all the tracks passed through the detection layer.

To compare the similarity of each LET curve or compare the similarity of the secondary particle yields, an evaluation index (EI) is defined for ith LET bins or i-types of secondary particles, as given in Equation (1). In the EI definitions, LET_i is the differential fluence in the ith LET bin and Y_i is the secondary particle yield at the test condition. $A_{ref,i}$ is the corresponding quantity at the reference condition, which is simulated from the LANSCE broad band neutron spectrum. To prevent dividing by zero, any $A_{test, i}$ with $A_{ref,i} = 0$ is ignored. In LET cases, the bin size for analysis was 0.2 MeV-cm²/mg and the counts were analyzed using a log scale.

EI is defined as the root mean square of relative error as follows:

$$EI = \sqrt{\frac{\sum_{i=1}^{N} \left[\frac{(A_{test, i} - A_{ref, i})}{A_{ref, i}}\right]^2}{N}}$$
(1)

here A_i is either LET_i or Y_i . The smaller EI will indicate better equivalency between two sets of data. The EI will be zero if the test protons generate identical LET differential fluences compared to those generated by the LANSCE neutron, that is, $(A_{test, i} - A_{ref, i}) = 0$, the same for secondary particle yield comparisons.

3. Results and Discussions

To compare the equivalence of neutrons and protons in SEE testing for the layer structure. LET, secondary yield, and energy deposited are evaluated in this work. Additionally, the effects of SiGe are also considered.

3.1. LET Difference between Neutrons and Protons

To examine if protons can be used to replace neutrons for SEE testing, the most important consideration is the equivalence of the LET spectrum as LET is a key determining parameter for the SEE. Figure 3 shows the LET spectra of the structure without SiGe being irradiated by protons and neutrons.



Figure 3. Linear energy transfer (LET) spectra in a structure without silicon-germanium (SiGe) irradiated by 63, 105, 150, 200, and 230 MeV proton and LANSCE neutron.

The LET spectra of the examined geometry irradiated with LANSCE neutron and selected monoenergetic protons were plotted in Figure 3. The largest visible difference in the LET spectra is below 1 MeV-cm²/mg, where protons generated 1000 times more events than neutrons did. Due to the low LET, this visible difference has minimal impact on single event effects, whilst it could cause the total ionization dose (TID) effects under prolonged radiation exposure. However, the cross section of the SEE can be altered by TID as described by Schwank et al. [19] and Lorne et al. [20].

We further compared the LET spectra of 200 MeV proton and the LANSCE neutron for LET larger than 1 MeV-cm²/mg. The differential fluence was in good agreement in LETs between 1 to 10 MeV-cm²/mg but was slightly deviated in LETs larger than 10 MeV-cm²/mg. This phenomenon can be explained with the help of Figure 4, in which the LET was plotted for several major secondary particles. In parentheses, the first symbol represents incident particles and the second symbol represents particles that contribute to the LET. For example, (n, He) means that the helium is generated by the LANSCE neutron.



Figure 4. The LET contribution from He, Mg, and Al generated by the 200 MeV proton and the LANSCE neutron. In parentheses, the first symbol represents incident particles and the second symbol represents particles that contribute to the LET.

In the LETs between 1 to 10 MeV-cm²/mg, events were mainly caused by helium ions, which were mostly due to the elastic interactions of high-energy particles, regardless of whether they were neutrons or protons. For LETs more than 10 MeV-cm²/mg, 200 MeV protons gave a higher differential fluence than the LANSCE neutron because protons generate more heavy secondary ions such as aluminum and magnesium. The LANSCE neutron produces very few of these secondary particles because most of the LANSCE neutron shown in Figure 1 is less than 10 MeV which is below the threshold energy of these nuclear interactions.

The LET spectra from the studied structure irradiated by lower proton energy are rarely used, but we included them in our work (see Figure 5). In these low-energy proton irradiations, the differential fluence in LET is 10,000 times higher than neutrons for LET lower than 0.5 MeV-cm²/mg and five times higher for LETs between 1 to 10 MeV-cm²/mg. On the other hand, for LETs larger than 10 MeV-cm²/mg, low-energy protons give less events. Therefore, from the above results, our further evaluation will focus on the protons with energy higher than 63 MeV.



Figure 5. LET spectra in a structure without SiGe from 10, 30, 50, 63, and 200 MeV protons and LANSCE neutron.

In comparison to the results from Hiemstra et al. [21], the LET distribution in our work was much wider because the simulation of all secondary particles was performed in our study, which means that both the ionization energy loss and the nuclear interactions were simulated. Therefore, our simulations are expected to be more accurate, but it is time-consuming (takes 2–3 days per energy per condition in a computer with Intel I9-9900k CPU working at 4600 MHz and two dual channels 8 GB RAM working at 3000 MHz). The uncertainty in our simulation for the LET spectra shown in Figures 3 and 4, is quantified using the coefficient of variation (C_v). We found that the C_v is less than 10% for LETs lower than 6 MeV-cm²/mg. However, if the LET is greater than 40 MeV-cm²/mg, C_v is between 30% and 70%, due to the small number of events with these LETs. To be noted, compared pair with high C_v may contribute more to the EI calculation, so that the LETs larger than 6 MeV-cm²/mg will dominate our conclusion about beam equivalency.

Another comparison is with the work from Turflinger et al. [22]; our results and theirs agree well for LETs lower than 15 MeV-cm²/mg. For higher LETs, no comparison can be made because the work of Turflinger et al. has a 5 μ m Pb/Au layer which is not present in this study.

The EI evaluation of the LET spectra is shown in Table 1, which shows that the 200 MeV proton has a LET spectrum with the best equivalence compared to the LANSCE neutron. The EI decreases with increasing proton energy, reaching the minimum at 200 MeV and increased at 230 MeV, with the exception for the 150 MeV proton, which may be questionable owing to the presence of a switch point for the hadron interaction around 150 MeV [14] in Geant4. The results shown in Table 1 are consistent with Figure 5 where 63 MeV proton gives higher differential fluence than the neutron, and 200 MeV proton gives lower differential fluence than the neutron in LETs < 10 MeV-cm²/mg. Of course, it is also possible that the best proton to replace the LANSCE neutron is with an energy between 105 and 200 MeV. Alternatively, a mix of different proton energies could also provide a better equivalence. All these possibilities are explored later.

Table 1. Evaluation index (EI) for LET in layer structure without SiGe.

	LANSCE	63 MeV	105 MeV	150 MeV	200 MeV	230 MeV
	Neutron	Proton	Proton	Proton	Proton	Proton
EI	0	0.290	0.274	0.296	0.250 *	0.285

* Indicates the best choice.

3.2. Secondary Particle Yield Difference between Neutron and Proton

The secondary particle species can not only produce a different LET but also change the semiconductor properties. In this study, the secondary particles with Z = 2-80 were analyzed. Figure 6 shows the secondary particle yields in structures without SiGe when it is irradiated by 63, 105, 150, 200, and 230 MeV protons and LANSCE neutron, respectively.



Figure 6. The secondary particle yields in structure without SiGe irradiated by 63, 105, 150, 200, and 230 MeV protons and LANSCE neutron.

In Figure 6, five groups can clearly be identified, namely alpha group, O group, Si group, Cu group, and W group, from left to right. Between copper and tungsten groups, there are some events from the cleavage fragments of W. In the secondary particle yields, the highest peak is at Z = 2, which is helium or alpha particles resulting from elastic interaction. The next two peaks, at Z = 6 and 14, are from SiO₂.

It can be seen in Figure 6 that the secondary particles distribution of the neutrons is narrower than that of the protons. The reason is that the energy of most neutrons is too low to have a spallation event. Another difference is that for Z > 14, 200 MeV protons generate more secondary particles than neutrons, but for 8 < Z < 14, neutrons give more events. The difference is mostly from the last layer of the structure, which is SiO₂. In the Z = ~70, which are made of tungsten, high-energy protons have much higher potential to generate secondary particles than the low-energy protons or even neutrons. For secondary particle yields, the C_v is dependent on the secondary particle species. For Z < 14, the C_v is less than 10%, but for heaver ions, some yields are less than 10 counts per 10⁹ incidents, and this makes the C_v go up to 60%. For a few channels, the C_v is even 100% because only one count is observed.

EI evaluation of the secondary particles yield is shown in Table 2, and again 200 MeV protons and the LANSCE neutron have the most similar secondary particle yields. Similar to the case of LETs, 63 MeV proton has the worst EI in secondary particle yields. In Figure 6, the 63 MeV proton in the Z range between 18 and 25 contributed fewer secondary ions, which are copper spallation fragments. In Z between 65 and 70, the 63 MeV proton also has fewer secondary yields. Rummana et al. reported that secondary particle yields are higher for protons with higher energy [23].

	LANSCE Neutron	63 MeV Proton	105 MeV Proton	150 MeV Proton	200 MeV Proton	230 MeV Proton		
EI	0	0.560	0.544	0.543	0.405 *	0.443		
* Indicates the best choice.								

Table 2. EI for secondary particle yields in layer structure without SiGe.

In Figure 6, 200 and 230 MeV protons typically gave more yields than the LANSCE neutron, but 63, 105, and 150 MeV protons gave less. It is possible that mixing different proton energies could lead to better neutron equivalence.

Therefore, from both Tables 1 and 2, 200 MeV proton radiation is closer to neutron radiation, and this concurs with suggestions from NASA (Washington, DC, USA).

3.3. LET Difference between Layer Structures with and without SiGe

The LET spectra for the LANSCE neutron and 63 and 230 MeV protons with and without SiGe were plotted in Figure 7. The difference in the overall spectra between the structures with and without SiGe is insignificant except for the LET value greater than 20 MeV-cm²/mg. LANSCE neutron and 63 MeV proton give lower differential fluence when the SiGe layer is added, but 230 MeV proton gives a larger differential fluence. This is because with high-energy protons, the yields of alpha and light ions correlate with the Z of an incident target. Since Ge has a larger Z than most of the materials in our structures, being four times larger than the Z of O and 2.3 times larger than the Z of Si, we observed more counts for the structure with SiGe in the lower LET. With low-energy protons, however, it is difficult to have spallation and generate secondary ions [24]. In addition, Ge has a larger neutron absorption coefficient than silicon [25,26], hence some neutrons were absorbed by the SiGe layer. Therefore, in the case of the LANSCE neutron, the events with LETs less than 0.1 MeV-cm²/mg are somewhat lower when SiGe is added.



Figure 7. LET spectra of the structure with and without SiGe irradiated by 63 and 230 MeV protons and LANSCE neutron. The plot is in log-log scale.

3.4. Secondary Particle Yields Difference between Layer Structure with and without SiGe

Figure 8 shows the difference in secondary yields between the structure with and without SiGe layer. At Z between 30 and 32, which mostly come from Ge (Z = 32), the cases with SiGe give much higher yields than the cases without SiGe. The reason is that in cases without Ge, these secondary particles with Z between 30 and 32 can only be generated in the W layer (Z = 74) with a very low probability, thus the yield is much lower compared to the number of secondary particles of another Z. In Z between 35 and 45, the cases without SiGe give higher yields because the Ge can stop the

movement of the heavy secondary particles due to the high Z and density of Ge. In comparison to the particle yields with Z < 30, however, the difference in secondary yield cannot be recognized, since these particles only make up less than a thousandth of all secondary particles.



Figure 8. The secondary particle yields in the structure with and without SiGe irradiated by 63 and 230 MeV protons and LANSCE neutron.

Tables 3 and 4 giving the EI evaluation on LETs and secondary particle yields of the structure with SiGe layer irradiated by the LANSCE neutron and selected monoenergetic protons. Similar to the results shown in Tables 1 and 2, the 200 MeV proton gives the lowest EI which means the best neutron equivalence.

	LANSCE Neutron	63 MeV Proton	105 MeV Proton	150 MeV Proton	200 MeV Proton	230 MeV Proton		
EI	0	0.237	0.256	0.258	0.228 *	0.257		

Table 3. EI for LET in layer structure with SiGe.

* Indicates	the best choice.
-------------	------------------

	LANSCE Neutron	63 MeV Proton	105 MeV Proton	150 MeV Proton	200 MeV Proton	230 MeV Proton		
EI	0	0.550	0.541	0.524	0.381 *	0.533		
* Indicates the best choice.								

Table 4. EI for secondary particle yields in layer structure with SiGe.

3.5. Energy Deposited Difference between Neutrons and Protons

In addition to LET, the energy deposition in the total devices is important for the study of SEE. Since a proton is an ionizing radiation, it releases energy when it passes the target. The energy deposited in the detection layer was calculated and shown in Tables 5 and 6 for structures with and without SiGe.

	LANSCE Neutron	63 MeV Proton	105 MeV Proton	150 MeV Proton	200 MeV Proton	230 MeV Proton
Energy deposited (GeV) C _v <0.01%	2.7019	15,910	10,680	8213.4	6750.3	6165.4
LET >1 (counts) C _v <0.7%	28,570	38,260	30,070	25,730	31,500	29,960
LET >10 (counts) C _v <3%	1200	2500	1680	1370	2310	1920
Energy deposited/LET >1 (keV) $C_v < 3\%$	94.6	41,500	35,500	31,900	21,400	20,500
Energy deposited/LET >10 (MeV) C _v <4.2%	2.25	636	635	599	292	321

Table 5. Energy deposition analysis results for the layer structure without SiGe for 10^{10} neutron/proton incident.

LET is in unit of MeV-cm²/mg.

Table 6. Energy deposition analysis results for the layer structure with SiGe for 10^{10} neutron/proton incident.

	LANSCE Neutron	63 MeV Proton	105 MeV Proton	150 MeV Proton	200 MeV Proton	230 MeV Proton
Energy deposited (GeV) Cv <0.01%	2.4761	15,956	10,706	8232.0	6765.3	6181.3
LET >1 (counts) Cv <0.7%	27,460	36,700	30,350	26,010	32,040	31,510
LET >10 (counts) Cv <3.2%	980	2360	1680	1280	2160	2360
Energy deposited/LET >1 (keV) Cv <3.3%	90.2	43,500	35,300	31,600	21,100	19,600
Energy deposited/LET >10 (MeV) Cv <4.6%	2.52	676	637	643	313	261

LET is in unit of MeV-cm²/mg.

For the case without SiGe, Table 5 shows that 63 MeV protons are found to have more events with LET > 1 and 10 MeV-cm²/mg than other incident particles, and they also cause the most energy deposition. This is expected as the lower energy will result in higher deposited energy since the stopping power is inversely proportional to the kinetic energy [24]. Calculating the energy deposited for generating an event, 200 MeV and 230 MeV give better efficiency (i.e., lower dose with higher LET counts). In comparison to neutrons, proton irradiation gives off over 200 times more energy deposited.

Compared to the results of structures with (Table 5) and without (Table 6) SiGe, both LANSCE neutron and protons show the differences on energy deposited and event number. For LET > 1 MeV-cm²/mg, a decrease of 4% in the secondary particle yields is observed, and for LET > 0 MeV-cm²/mg, the decrease is 20% in the LANSCE neutron case. These decreases are due to the presence of germanium which has a larger neutron absorption cross-section than other materials in this study [25,26].

In the proton cases, 63 MeV proton also has a 4% decrease in secondary yields from LET > 1 MeV-cm²/mg and a 6% decrease for LET > 10 MeV-cm²/mg. For 230 MeV proton, however, the secondary yield does not lead to a decrease, but rather to an increase both with LET > 1 MeV-cm²/mg and LET > 10 MeV-cm²/mg. This is because of the spallation which generates heavy secondary ions in the cases of proton irradiation. This spallation has its cross-section positively correlate to the incident energy and the Z of the target [19].

4. Conclusions

From the Monte Carlo studies in this work, in comparing the LET spectra and secondary particles yield from the proton and neutron radiation, we found that 200 MeV proton radiation has the closest resemblance to the neutron radiation, which concurs with suggestions from NASA. However, even with this close proton radiation, several differences present between proton and neutron radiation are as follows: First, proton radiation produces high secondary particles yield for LET > 15 MeV-cm²/mg, and neutron hardly has LET > 10 MeV-cm²/mg. Second, the secondary particles distribution is broader for the case of proton radiation. Third, proton radiation produces more secondary particles with Z > 14 whilst neutron radiation produces more secondary particles with 8 < Z < 14. Fourth, the energy deposited from proton radiation is around 300 times higher than neutron in the same flux. Fifth, the presence of SiGe does not affect the secondary particles yield for proton radiation, but it is decreased for neutron radiation. This implies that the strengthen of radiation robustness with the addition of SiGe cannot be seen with proton radiation.

In this study, we only focus on some commonly used monoenergetic protons in several testing protocols. As presented in the results, no monoenergetic proton can reproduce exactly the secondary particle LET and yield spectra to that of the LANSCE broad band neutron. However, it may be possible that mixing energies of protons can create better equivalence. Further study using range (energy) modulation technique to generate wider proton spectrum will be conducted to explore this possibility.

As LET and secondary particles yield can affect SEE testing, how the above-mentioned five differences will affect the SEE testing results are as of yet unknown. The answers can only be known through either subsequent proton or neutron testing or SEE simulation on semiconductor devices with LET and secondary particles yield distribution as obtained from the Geant4 simulation. On the other hand, as proton radiation seems to be more stringent than neutron radiation, one may use proton radiation tests as a higher calling to the radiation robustness of integrated circuits, with the expense of possibly higher design and fabrication costs. All these future works will be necessary in order to ascertain the equivalence or acceleration of neutron and protons radiation for SEE testing.

Author Contributions: Conceptualization, C.M.T. and T.-C.C.; methodology, C.-J.T. and C.-C.L.; Writing—original draft preparation, Y.C.; project administration, C.M.T.; writing—review and editing, C.M.T. and T.-C.C.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Taiwan Semiconductor Manufacturing Company JDP project. And Chang Gung Medical Re-search Program under projects CIRPD110022, BMRP736, CIRPD2F0024, and CIRPD210012.

Acknowledgments: This work was technically supported by the Particle Physics and Beam Delivery Core Laboratory of the Institute for Radiological Research, Chang Gung University/Chang Gung Memorial Hospital.

Conflicts of Interest: All authors have no conflict of interest to the organizations mentioned in the paper.

References

- 1. Dong, A.X.; Gwinn, R.P.; Warner, N.M.; Caylor, L.M.; Doherty, M.J. Mitigating bit flips or single event upsets in epilepsy neurostimulators. *Epilepsy Behav. Case Rep.* **2016**, *5*, 72–74. [CrossRef] [PubMed]
- Seifert, N.; Jahinuzzaman, S.; Velamala, J.; Ascazubi, R.; Patel, N.; Gill, B.; Basile, J.; Hicks, J. Soft error rate improvements in 14-nm technology featuring second-generation 3D tri-gate transistors. *IEEE Trans. Nucl. Sci.* 2015, 62, 2570–2577. [CrossRef]
- Wie, B.S.; LaBel, K.A.; Turflinger, T.L.; Wert, J.L.; Foster, C.C.; Reed, R.A.; Kostic, A.D.; Moss, S.C.; Guertin, S.M.; Pankuch, M.; et al. Evaluation and Application of U.S. Medical Proton Facilities for Single Event Effects Test. *IEEE Trans. Nucl. Sci.* 2015, *62*, 2490–2497. [CrossRef]
- 4. O'Neill, P.M.; Badhwar, G.D.; Culpepper, W.X. Internuclear cascade-evaporation model for LET spectra of 200 MeV protons used for parts testing. *IEEE Trans. Nucl. Sci.* **1998**, *45*, 2467–2474. [CrossRef] [PubMed]
- Javanainen, A.; Malkiewicz, T.; Perkowski, J.; Trzaska, W.H.; Virtanen, A.; Berger, G.; Hajdas, W.; Lyapin, V.; Kettunen, H.; Mutterer, M.; et al. Linear Energy Transfer of Heavy Ions in Silicon. *IEEE Trans. Nucl. Sci.* 2007, 54, 1158–1162. [CrossRef]

- 6. Dodd, P.E.; Shaneyfelt, M.R.; Felix, J.A.; Schwank, J.R. Production and propagation of single-event transients in high-speed digital logic ICs. *IEEE Trans. Nucl. Sci.* **2004**, *51*, 3278–3284. [CrossRef]
- Bagatin, M.; Gerardin, S.; Paccagnella, A.; Visconti, A.; Virtanen, A.; Kettunen, H.; Costantino, A.; Ferlet-Cavrois, V.; Zadeh, A. Single Event Upsets Induced by Direct Ionization from Low-Energy Protons in Floating Gate Cells. *IEEE Trans. Nucl. Sci.* 2017, 64, 464–470. [CrossRef]
- Acosta Urdaneta, G.C.; Bisello, D.; Esposito, J.; Mastinu, P.; Prete, G.; Silvestrin, L.; Wyss, J. ANEM: A rotating composite target to produce an atmospheric-like neutron beam at the LNL SPES facility. In *International Journal of Modern Physics: Conference Series*; World Scientific Publishing Company: Singapore, 2016; Volume 44, p. 1660207. [CrossRef]
- Agostinelli, S.; Allison, J.; Amako, K.A.; Apostolakis, J.; Araujo, H.; Arce, P.; Asai, M.; Axen, D.; Banerjee, S.; Behner, F.; et al. Geant4—A simulation toolkit. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* 2003, 506, 250–303. [CrossRef]
- Foley, K.; Seifert, N.; Velamala, J.B.; Bennett, W.G.; Gupta, S. IRT: A modeling system for single event upset analysis that captures charge sharing effects. In Proceedings of the 2014 IEEE International Reliability Physics Symposium, Waikoloa, HI, USA, 1–5 June 2014; p. 5F.1. [CrossRef]
- 11. Weller, R.A.; Mendenhall, M.H.; Reed, R.A.; Schrimpf, R.D.; Warren, K.M.; Sierawski, B.D.; Massengill, L.W. Monte Carlo Simulation of Single Event Effects. *IEEE Trans. Nucl. Sci.* **2010**, *57*, 1726–1746. [CrossRef]
- Allison, J.; Amako, K.; Apostolakis, J.; Arce, P.; Asai, M.; Aso, T.; Bagli, E.; Bagulya, A.; Banerjee, S.; Beck, B.R.; et al. Recent developments in Geant4. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* 2016, 835, 186–225. [CrossRef]
- Truscott, P.; Lei, F.; Dyer, C.S.; Frydland, A.; Clucas, S.; Trousse, B.; Hunter, K.; Comber, C.; Chugg, A.; Moutrie, M. Assessment of neutron- and proton-induced nuclear interaction and ionization models in Geant4 for Simulating single event effects. *IEEE Trans. Nucl. Sci.* 2004, *51*, 3369–3374. [CrossRef]
- 14. Geant4-Collaboration. Book For Application Developers, Rev10.4 ed.; CERN: Geneva, Switzerland, 2019.
- Apostolakis, J.; Folger, G.; Grichine, V.; Heikkinen, A.; Howard, A.; Ivanchenko, V.; Kaitaniemi, P.; Koi, T.; Kosov, M.; Ribon, A.; et al. Progress in hadronic physics modelling in Geant4. *J. Phys. Conf. Ser.* 2009, 160. [CrossRef]
- Tohka, J.; Reilhac, A. A Monte Carlo Study of Deconvolution Algorithms for Partial Volume Correction in Quantitative PET. In 2006 IEEE Nuclear Science Symposium Conference Record; IEEE: Piscataway, HJ, USA, 2006; pp. 3339–3345.
- 17. Chiang, Y.; Tan, C.M.; Tung, C.-J.; Chao, T.-C. Lineal energy of proton in silicon by a microdosimetry simulation. *Radiat. Phys. Chem.* **2020**. submitted.
- 18. Hsing, C.-H.; Cho, I.C.; Chao, T.-C.; Hong, J.-H.; Tung, C.-J. GNP enhanced responses in microdosimetric spectra for 192Ir source. *Radiat. Meas.* **2018**, *118*, 67–71. [CrossRef]
- Schwank, J.R.; Dodd, P.E.; Shaneyfelt, M.R.; Felix, J.A.; Hash, G.L.; Ferlet-Cavrois, V.; Paillet, P.; Baggio, J.; Tangyunyong, P.; Blackmore, E. Issues for single-event proton testing of SRAMs. *IEEE Trans. Nucl. Sci.* 2004, 51, 3692–3700. [CrossRef]
- 20. Erhardt, L.S.; Haslip, D.S.; Cousins, T.; Buhr, R.; Estan, D. Gamma enhancement of proton-induced SEE cross section in a CMOS SRAM. *IEEE Trans. Nucl. Sci.* **2002**, *49*, 2984–2989. [CrossRef]
- 21. Hiemstra, D.M.; Blackmore, E.W. Let spectra of proton energy levels from 50 to 500 mev and their effectiveness for single event effects characterization of microelectronics. *IEEE Trans. Nucl. Sci.* 2003, *50*, 2245–2250. [CrossRef]
- Turflinger, T.L.; Clymer, D.A.; Mason, L.W.; Stone, S.; George, J.S.; Koga, R.; Beach, E.; Huntington, K. Proton on Metal Fission Environments in an IC Package: An RHA Evaluation Method. *IEEE Trans. Nucl. Sci.* 2017, 64, 309–316. [CrossRef]
- 23. Rummana, A.; Barlow, R. Simulation and parameterisation of spallation neutron distributions. In *4th Workshop on ADS and Thorium*; SISSA Medialab: Trieste, Italy, 2017; p. 023.
- 24. Segrè, E.; Staub, H.; Bethe, H.A.; Ashkin, J. *Experimental Nuclear Physics. Volume I Volume I.*; John Wiley & Sons: New York, NY, USA; Chapman & Hall (in English): London, UK, 1953.

- 25. Hodgson, M.; Lohstroh, A.; Sellin, P.; Thomas, D. Neutron detection performance of silicon carbide and diamond detectors with incomplete charge collection properties. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2017**, *847*, 1–9. [CrossRef]
- 26. Aguayo, E.; Kouzes, R.; Orrell, J.; Reid, D.; Fast, J. *Optimization of the Transport Shield for Neutrinoless Double Beta-decay Enriched Germanium*; Pacific Northwest National Laboratory: Richland, WA, USA, 2012. [CrossRef]



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).