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Comparison of single-event upset generated by heavy ion and pulsed laser

Bin LIANG[1*], Ruiqiang SONG[1], Jianwei HAN[2], Yaqing CHI[1], Rui CHEN[2], Chunmei HU[1], Jianjun CHEN[1], Yingqi MA[2] & Shipeng SHANGGUAN[2]

[1] *College of Computer, National University of Defense Technology, Changsha* 410073*, China;*
[2] *Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing* 100080*, China*

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Abstract Single-event upset (SEU) is investigated using heavy ion and pulsed laser. The measured SEU cross sections of D and DICE flip-flops are compared. Measurement results indicate pulsed laser is capable of inducing similar SEU to those induced by heavy ion. 3D-TCAD simulation is performed to investigate the factors to impact pulsed laser induced SEU. Simulation results show that the beam spot size significantly impacts SEU cross sections in both low and high laser energy while the variation of the equivalent LET only impacts SEU cross sections in the low laser energy.

Keywords single-event upset, charge sharing, cross sections, heavy ion, pulsed laser

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1 Introduction

Single-event upset (SEU) has become an important reliability concern for nanoscale technologies [1, 2]. Reduced nodal capacitance and supply voltage decrease the critical charge to cause SEU. Close proximity of transistors results in charge sharing at multiple nodes. These phenomena increase the SEU sensitivity of the conventional flip-flops by orders of magnitude. Some work has reported the conventional flip-flops are more sensitive to SEU at advanced CMOS technologies [3]. Therefore, it is vital to character SEU of flip-flops through simulation or experiment methods.

Pulsed laser technique has become an important tool to investigate single-event effect (SEE) [4]. Since it is capable of inducing similar effects to those induced by heavy ions, a wide range of circuit types have been investigated using pulsed laser [5–7]. In previous work, many SEU measurement results have been reported using pulsed laser technique. For example, pulsed laser technique was widely used to character and mapping the SEU sensitivity of flip-flops or SRAMs [8–10]. However, because of the large beam spot and the uncertain equivalent linear energy transfer (LET) for the laser energy, there is still a challenge to compare SEU measurement results generated by heavy ion and pulsed laser. Although some work has been reported the SEU measurements under heavy ion and pulsed laser radiation environment [11, 12],

* Corresponding author (email: liangbin110@126.com)

Table 1 Test chips used in the experiment

Test no.	Circuit cell	Core voltage (V)	Other feature
Test-A	D flip-flop	1.0	Dual-well
	D flip-flop	1.0	Triple-well
	DICE flip-flop	1.0	Dual-well
	DICE flip-flop	1.0	Triple-well
Test-B	D flip-flop	1.2	Dual-well
	DICE flip-flop	1.2	Dual-well

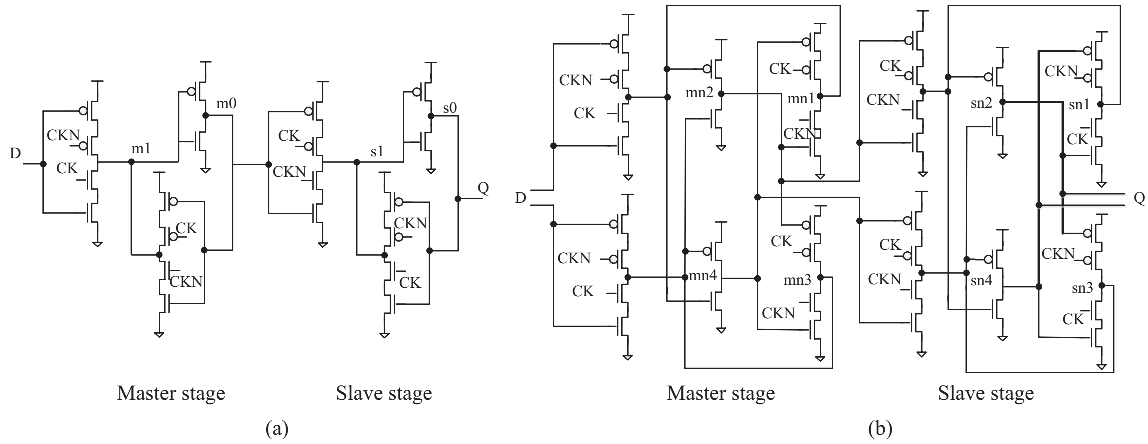

Figure 1 The schematics of (a) the conventional D flip-flop and (b) the conventional DICE flip-flop.

they only depict SEU of the circuits with large device size. Therefore, it is necessary to investigate and compare SEU measurement results between heavy ion and pulsed laser at advanced CMOS technologies.

In this paper, the SEU sensitivity of the conventional D and DICE flip-flops are compared under heavy ion and pulsed laser. Pulsed laser induced SEU show obvious discrepancies in the low laser energy. However, it is capable of inducing similar SEU to those induced by heavy ions with the laser energy increases. Three-dimensional technology computer aided design (3D-TCAD) simulation tool is performed to investigate the factors to impact pulsed laser measurement results. Simulation results show that the beam spot size and the variation of the equivalent LET are the main reasons to impact pulsed laser induced SEU.

2 Test chips design and experiment setup

2.1 Test chips design

Tow test chips were designed and fabricated based on the commercial 65 nm CMOS technology. Design details of these test chips are shown in Table 1. Test-A and Test-B were constructed by the conventional D and DICE flip-flops. The schematics of the D and DICE flip-flops are shown in Figure 1. Although Test-A and Test-B contained the same flip-flops, they were fabricated by the different manufacturers.

The D flip-flop can be upset when the incident ion or pulsed laser strikes a single storage node. The DICE flip-flop is immune to SEU at the single storage node, but can be upset if any sensitive node-pairs collect charge simultaneously. Based on the D and DICE flip-flops, SEU caused by both charge collection of the single node and charge sharing between multiple nodes can be investigated. The schematic of Test-A and Test-B is shown in Figure 2(a). The layout topology of these test chips is shown in Figure 2(b). Test-A and Test-B contained several shift registers. Each shift register contained 2048 stages flip-flops with the data and clock tree. Once one stage of the shift register chain was corrupted by heavy ion or pulsed laser, the subsequent ones in the chain propagated the upset value until it was read out from the output pin.

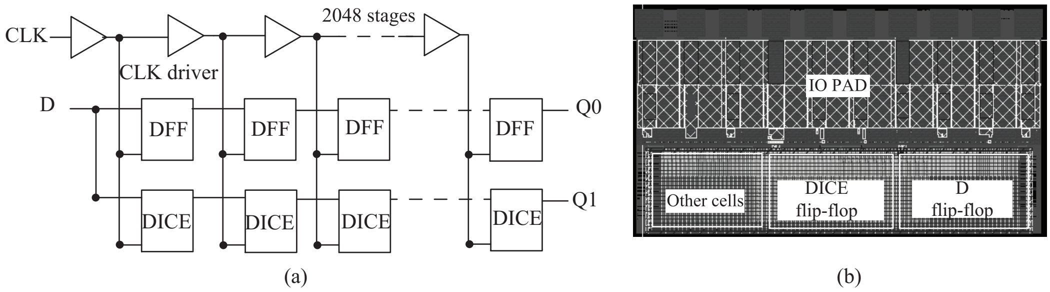

Figure 2 The schematics of (a) the test circuit and (b) the whole layout.

Table 2 Heavy ions used in the experiment

Ion	Energy at the silicon surface (MeV)	Effective LET ($MeV{\cdot}cm^2/mg$)	Range (μm)
Cl	165	11.3	51.8
Ti	185	21.2	37.9
Ge	205	37.1	35.5
Bi	923.2	99.8	53.7

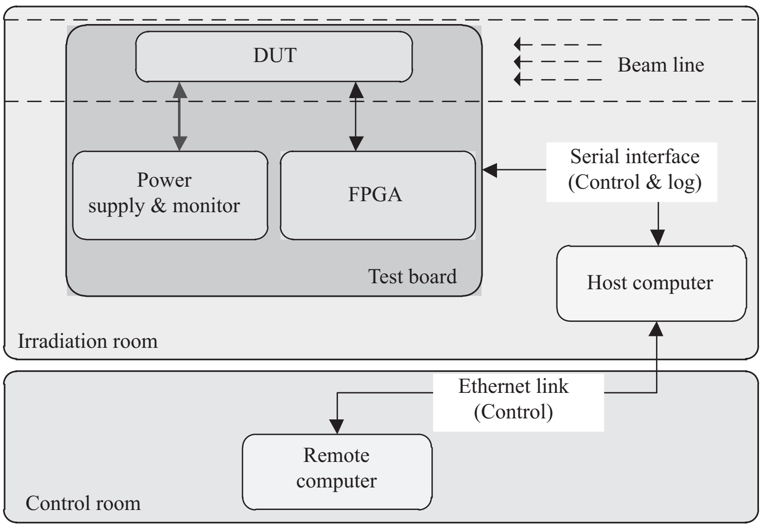

Figure 3 The structure of the heavy ion experiment setup.

2.2 Heavy ion experiment setup

Heavy ion experiment was conducted at the HI-13 tandem accelerator in China institute of atomic energy and the heavy ion research facility in Lanzhou (HIRFL) cyclotrons in institute of modern physics, Chinese academy of sciences. The characteristics of heavy ions used in the experiment are listed in Table 2. The incident ion dose rate was 1×10^4 ions/cm$^2 \cdot$ s and the fluence in each incident ion was 1×10^7 ions/cm^2. The basic heavy ion experiment setup is shown in Figure 3. Test chips were mounted on a test board, which also equipped a field-programmable gate array (FPGA). All the signal (input, output and clock) pins of each test chip were connected to FPGA. Error detection was implemented by FPGA and the error counts were exported to the computer by the serial interface.

Heavy ion induced SEU was measured with normal supply voltage and room temperature. The dynamic test mode was used to measure the SEU sensitivity of the D and DICE flip-flops. The test circuit was irradiated with solid 0 data or solid 1 data. Since the input data were fixed, soft errors owing to the clock tree were avoided. The upset in the clock tree may cause the data to shift forward without any error. Therefore, only flip-flop induced upset can cause SEU.

Table 3 Pulsed laser used in the experiment

Energy (nJ)	Equivalent LET (MeV·cm^2/mg)	Step size (μm)	Equivalent fluence (ions/cm^2)
0.70	25.3 ± 6.3	5	4×10^6
1.00	36.1 ± 9.0	5	4×10^6
2.96	106.9 ± 16.7	5	4×10^6

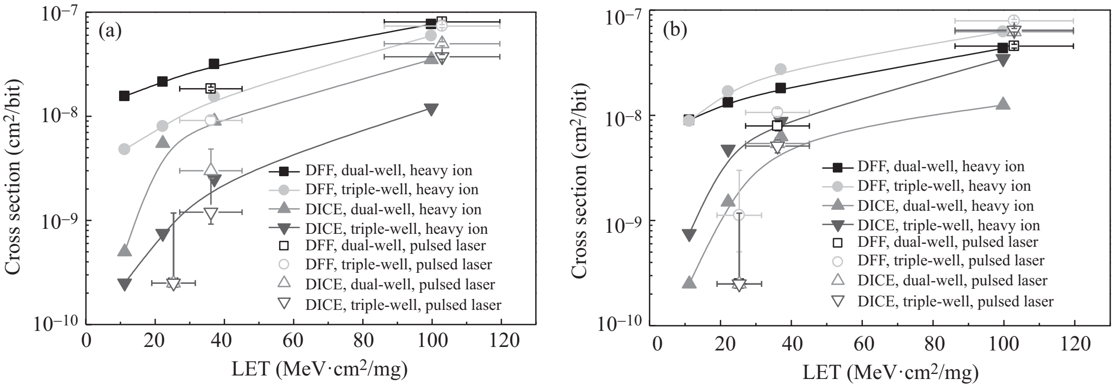

Figure 4 The measured SEU cross sections with (a) solid 0 and (b) solid 1 dynamic test mode in Test-A.

2.3 Pulsed laser experiment setup

Pulsed laser experiment was conducted at the PLSEE facility of National Space Science Center, Chinese Academy of Sciences. The laser wavelength was 1064 nm (single photon absorption) and the focused laser spot was about 1.7 μm at the target plane. The test chips were mounted on a three-dimensional motorized stage and the laser system was automated to scan the whole test chip region. The detailed schematic of the pulsed laser test system was described in our previous work [13].

To avoid the obstruction of metal lines in the front side of the test chips, the laser light was directed through the wafer from the back side. Table 3 shows the parameters used in pulsed laser experiment. Three laser energies were chosen which the calculated equivalent LET was similar to heavy ion. The equivalent LET was calculated based on the previous work and it has been validated in our previous work [13]. It is noteworthy that the range of the equivalent LET for laser energy was also calculated because it was difficult to obtain an accurate relationship between the laser energy and the equivalent LET. All the tests have been done with normal supply voltage and room temperature. The test mode and other test setup were consistent with heavy ion experiment.

3 Comparison of heavy ion and pulsed laser experiment results

The measured SEU cross sections in Test-A are shown in Figure 4. The SEU cross section is defined as the total number of SEUs captured by heavy ion or pulsed laser experiments divided by the fluence (1×10^7 ions/cm^2 for heavy ion and 4×10^6 ions/cm^2 for pulsed laser) and the stages of the shift register chain (2048). The X error bars represent the range of the equivalent LET for the laser energy. The Y error bars represent the 95% confidence intervals.

Based on the measurement results, pulsed laser induced SEU shows significant discrepancies in the equivalent low LET. The SEU cross section has about one order of magnitude lower compared with heavy ion results when the laser energy is 0.7 nJ. With the laser energy increases, pulsed laser induced SEU becomes significant. The measured SEU cross section shows a similar trend when the laser energy is 1.0 nJ. It also shows a slight higher when the laser energy is 2.96 nJ. The measured SEU cross sections in Test-B are shown in Figure 5. Similar with Test-A measurement results, pulsed laser induced SEU shows significant discrepancies in the equivalent low LET. However, a similar SEU trend is also observed

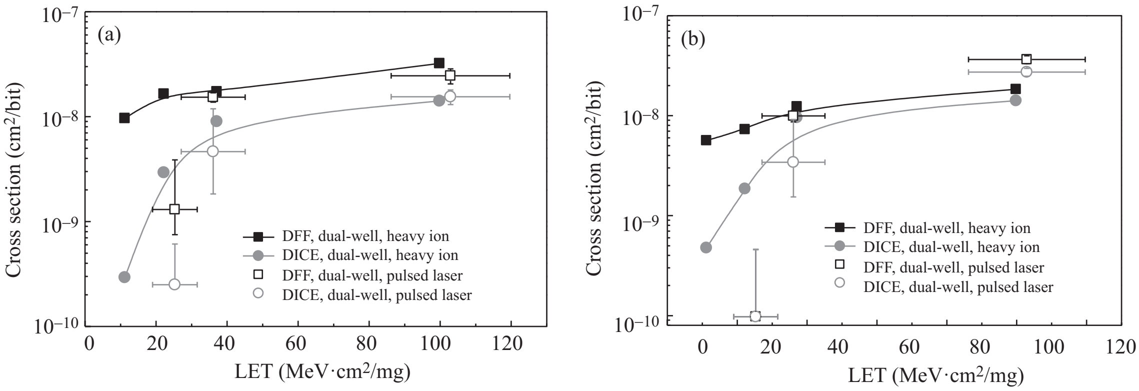

Figure 5 The measured SEU cross sections with (a) solid 0 and (b) solid 1 dynamic test mode in Test-B.

with the equivalent LET increases. Although Test-B was fabricated by the different manufacturer, pulse laser is also capable of inducing similar SEU with the laser energy increases.

The variation of the equivalent LET may be the main reason to cause the discrepancy of SEU cross sections in the low laser energy. When the laser energy is 0.7 nJ, the calculated equivalent LET is from 19 to 31.6 $\mathrm{MeV \cdot cm^2/mg}$. However, the actual equivalent LET is lower than the calculation values. Based on the measurement results, the actual equivalent LET is lower than the LET threshold of the DICE flip-flop (about 12 $\mathrm{MeV \cdot cm^2/mg}$) because pulsed laser is hard to cause SEU of the DICE flip-flop. The lower equivalent LET reduces the ionized charge generated by pulsed laser. The sensitive transistors are hard to collect enough charge and SEU is hard to occur. Therefore, the measured SEU cross sections show a significant lower when the laser energy is low.

When the laser energy is high enough, the variation of the equivalent LET slightly impacts the SEU cross section because the SEU cross sections begin to saturate. The beam spot size may be the main reason to cause a higher SEU cross sections. The large beam spot can impact more sensitive transistors. For the D flip-flop, the large beam spot enhances the carrier diffusion. The sensitive transistors are easier to collect more charge and cause SEU. For the DICE flip-flop, the large beam spot increases the range of charge sharing. The sensitive node-pairs have a higher probability to collect charge simultaneously. Therefore, the measured SEU cross sections are slight higher than heavy ion measurement results when the laser energy is high.

It is noteworthy that pulsed laser measurement results can also reveal SEU variations caused by the data pattern. In previous work, different input data significantly impacts the SEU sensitivity of flip-flops [1]. In our heavy ion measurement results, the SEU cross section of the dual-well DICE flip-flop is higher than that of the triple-well DICE flip-flop when the input data is solid 0. However, it shows an inverse measurement result when the input data is solid 1. Similar measurement results are also observed for the dual- and triple-well D flip-flop. Pulsed laser measurement results also show the similar SEU variation trend for the D and DICE flip-flop. Experiment results indicate pulse laser is capable of investigating the flip-flop sensitivity with different data patterns.

The additional deep-N-well (DNW) in triple-well process is the main reason to cause the SEU variations. The DNW decreases the collected charge of the sensitive PMOS transistor because it weakens the parasitic bipolar amplification effect of the PMOS transistor. However, the DNW increases the collected charge of the sensitive NMOS transistor because it enhances the parasitic bipolar amplification effect of the NMOS transistor [14]. Based on the latch structure used in this paper, the PMOS transistor is the main sensitive transistor when the input data is solid 0. Therefore, the DNW would decrease the sensitivity of the PMOS transistor and lead to decrease the SEU cross section of the triple-well flip-flop. On the contrary, the NMOS transistor is the main sensitive transistor when the input data is solid 1. The DNW enhances the sensitivity of the NMOS transistor and increases the SEU cross section of the triple-well flip-flop.

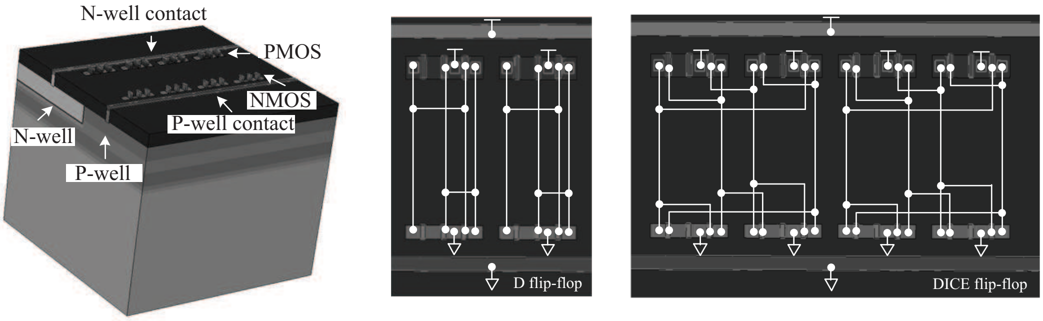

Figure 6 The TCAD models of the D and DICE flip-flops.

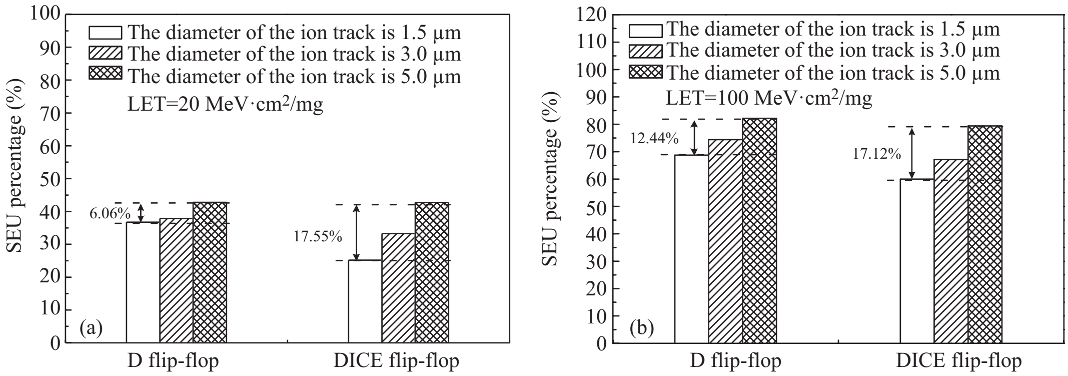

Figure 7 The simulated SEU percentage of the D and DICE flip-flops with different beam spot sizes. (a) The incident equivalent LET is 20 MeV $\cdot$ cm^2/mg; (b) the incident equivalent LET is 100 MeV $\cdot$ cm^2/mg.

4 Discussions

The SEU cross section under pulsed laser has an obvious discrepancy in the threshold region (low LET) while it is similar to heavy ion results in the saturation region (high LET). Pulsed laser induced SEU can be neglectable in the low energy while it becomes significant with the laser energy increases. Based on the measurement results, the beam spot size and the variation of the equivalent LET may be the main reasons to cause the discrepancy between heavy ion and pulsed laser results.

In our previous work, 3D-TCAD simulation tool was a useful means to investigate the physical mechanism of SEE [15–17]. To clearly understand the mechanisms, 3D-TCAD tool was performed to simulate pulsed laser induced SEU. The D and DICE flip-flops were represented as the TCAD models, as shown in Figure 6. The PMOS and NMOS transistors in each TCAD model were calibrated to match electrical characteristics obtained from standard compact models for the commercial 65 nm bulk technology. The transistor size, spacing and the well configuration were satisfied with the layout topology. The incident locations were set to along the transistors. The node voltages after each ion strike were simulated to determine the number of SEU. During TCAD simulation, the diameter of the beam spot size was set to 1.5, 3 and 5 μm, respectively. It was used to investigate pulsed laser induced SEU with different beam spot sizes. The incident equivalent LET value was set to about 20 and 100 MeV $\cdot$ cm^2/mg. It is noteworthy that the incident LET was about ± 6 and ± 16 MeV $\cdot$ cm^2/mg variations, respectively. It was used to investigate pulsed laser induced SEU with the variation of the equivalent LET.

Physical models used in TCAD simulation included Fermi-Dirac statistics, band-gap narrowing effect, Auger recombination, and doping dependent, electric field dependent, and carrier-carrier scattering mobility models. Unless otherwise specified, the default models and parameters were provided by Sentaurus TCAD vH-2013.03.

Figure 7 shows the simulated SEU percentage with different beam spot sizes. The SEU sensitivity of D and DICE flip-flops shows an obvious increase trend with the beam spot size increases. The SEU percentage of D and DICE flip-flops shows about 6% and 17% increase in both the equivalent low LET

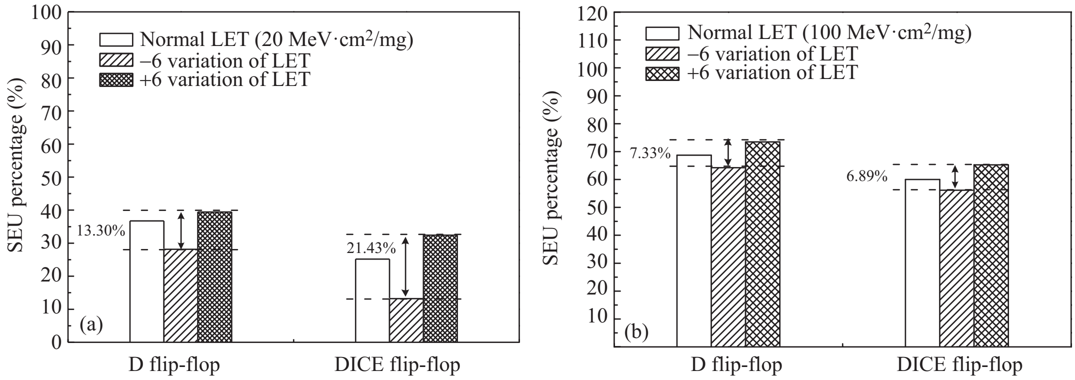

Figure 8 The simulated SEU percentage of the D and DICE flip-flops with the variation of the equivalent LET. (a) The incident equivalent LET is 20 $\mathrm{MeV\cdot cm^2/mg}$; (b) the incident equivalent LET is 100 $\mathrm{MeV\cdot cm^2/mg}$.

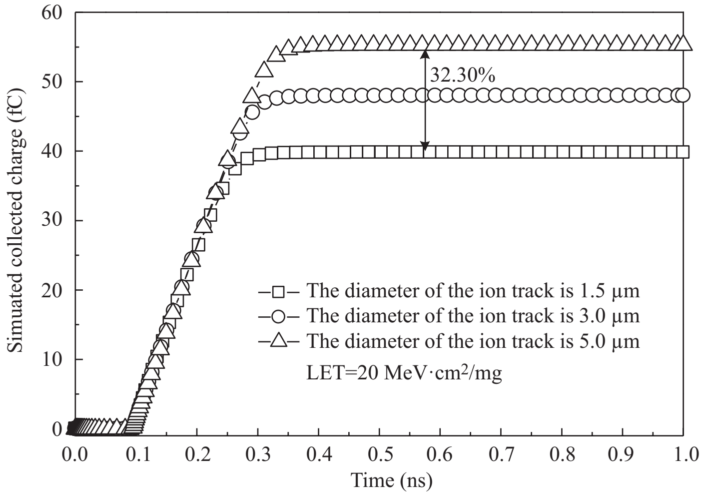

Figure 9 The simulated collected charge with different beam spot sizes.

and high LET. Simulation results indicate the beam spot significantly impact pulsed laser induced SEU in both low and high laser energy. The simulated SEU percentage with the variation of the equivalent LET is shown in Figure 8. The diameter of the beam spot size is fixed to 1.5 μm during TCAD simulations. Different from the beam spot size, the variation only significantly impact pulsed laser induced SEU when the laser energy is low. The simulated SEU shows more than 13% increase in the equivalent low LET while it has only about 7% change in the equivalent high LET. Simulation results indicate the variation of the equivalent LET mainly impact pulsed laser induced SEU when the laser energy is low.

The beam spot size and the variation of the equivalent LET significantly impact the collected charge of the sensitive transistors. For example, Figure 9 shows the simulated collected charge of the sensitive transistor with different beam spot size in the equivalent low LET. It shows more than 30% increase with the spot size increases. The flip-flops are easier to cause SEU due to the increased collected charge of sensitive transistors. It increases the SEU sensitivity of flip-flops and impacts the simulated SEU percentage in TCAD simulations. Therefore, the simulation results show a significant variation with the beam spot size and the equivalent LET change. When the LET is low, the variation of the simulated SEU percentage caused by the equivalent LET is larger than that caused by the beam spot size. However, an inverse measurement result is shown when the equivalent LET is high. Simulation results validate that the variation of the equivalent LET is the main reason to cause the discrepancy of SEU cross sections in the low laser energy while the beam spot size is the main reason to cause the discrepancy of SEU cross sections in the high laser energy.

It is noteworthy that the DICE flip-flop is more sensitive to the beam spot size and the variation of the equivalent LET. Charge sharing is the main reason to cause this discrepancy. For the D flip-flop, the basic mechanism to cause SEU is charge collection. For the DICE flip-flop, the basic mechanism to cause SEU is charge sharing because the DICE flip-flop is immune to SEU at the single node. The variation of the equivalent LET and the beam spot size significantly impact charge sharing. For example, when beam spot is from 1.5 to 3.0 μm in the equivalent low LET, it slightly impacts on the charge collection while it significantly increases the range of charge sharing. The enhanced charge sharing significantly increase SEU sensitive of the DICE flip-flop. The increase of the SEU percentage of DICE flip-flop is higher than that of the D flip-flop. Therefore, the DICE flip-flop is more sensitive to the beam spot size and the variation of the equivalent LET.

5 Conclusion

The SEU sensitivity of D and DICE flip-flops are investigated under heavy ion and pulsed laser. Measurement results show a significant discrepancy in the low laser energy and a similar SEU trend with the laser energy increases. The variation of the equivalent LET and the beam spot size are the main mechanism to cause the discrepancies in the low and high laser energies. 3D-TCAD simulation tool is performed to investigate and validate the factors to impact pulsed laser induced SEU. Simulation results indicate the beam spot size significantly impacts pulsed laser SEU measurement in both low and high laser energy while the variation of the equivalent LET only impacts pulsed laser SEU measurement in the low laser energy.

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Conflict of interest The authors declare that they have no conflict of interest.

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