Analysis of the Soft Error Rates on 65-nm SOTB and 28-nm UTBB FD-SOI Structures by a PHITS-TCAD Based Simulation Tool

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I. Abstract

We estimate the SERs of 65-nm SOTB(Silicon on Thin BOX) and 28-nm UTBB(Ultra Thin Body and BOX) FD-SOI processes by decreasing the supply voltage. Alpha, neutron irradiation experiments and Monte-Carlo based simulations are compared in this work. The SERs can be analyzed by the simulation tool with only layout pattern of test chips. The simulation results are consistent with the alpha and neutron irradiation measurement results.

II. Introduction

SEU (Single Event Upset) is caused by radiation induced charge collection at a single sensitive node, such as the drain region of a single transistor. Radiation-hardened circuits, such as Triple Modular Redundancy (TMR), or Dual Interlocked storage CEll (DICE)[1] have been employed to suppress the effects of charge collection at multiple circuit nodes. The charge collection mechanism has become more complex due to device shrinking and increasing circuit densities. Not only the drift and diffusion, also the bipolar effect become dominant when a single event occur in the circuit[2].

Silicon On Thin BOX (SOTB)[3] and Ultra Thin Body and BOX (UTBB)[4] are two kinds of FD-SOI with a thin BOX layer. It can suppress the charge collected into device. Thus, they have higher soft error tolerance than bulk structures. There is no dopant in the channel of FD-SOI. Variations are suppressed. The supply voltage of SOTB can be decreased to 0.4 V[5]. Thus, It is necessary to research the soft error tolerance of FD-SOI structure by supplying low power.

In this work, we analyze the alpha particle and neutron induced SERs on 65-nm SOTB and 28-nm UTBB latch by irradiation experiments and simulations. The Monte-Carlo based simulation tool is called PHITS-TCAD. The simulation tool is similar to the simulation tools such as MRED[6], IRT[7] and PHYSERD[8]. PHITS[9] is a kind of physics level simulator as Geant4. The neutron and alpha particle nuclear reactions can be run in PHITS only by inputting the layout date. It is possible to forecast the soft error tolerance before test chips fabrications and irradiation experiments by the proposed simulation system. The simulation results show that the soft error tolerance of 28-nm UTBB is 10x stronger than 65-nm SOTB when the supply voltage is 0.4 V. The soft error tolerance of FD-SOI structure become weaker by reducing the supply voltage. There is no soft error in the 28-nm UTBB structure when the supply voltage is larger than 0.5V according to the experimental results. The simulation results are consistent with alpha and neutron irradiation experimental results.

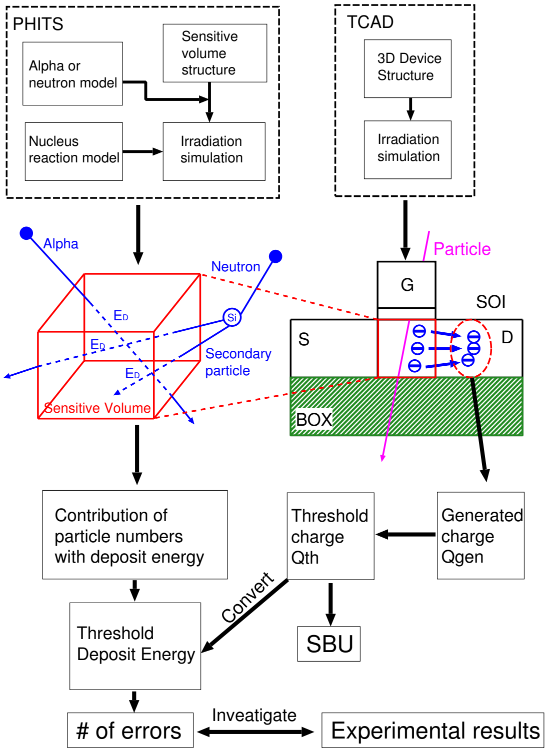


Fig. 1. Flow chart of the PHITS-TCAD simulation system.

This paper is organized as follows. Section III introduce the PHITS-TCAD simulation tool. We compare the simulations and alpha irradiation experimental results in section IV. Section V shows the neutron irradiation results. Section VI concludes this paper.

III. PHITS-TCAD Simulation Tool

A. How Does PHITS-TCAD Work

Fig. 1 portrays a flow chart of our simulation system by PHITS and TCAD. PHITS is a Monte-Carlo physics simulator. It is devoted to simulations of secondary ion generation via nuclear interaction of an incident particle with constituent atoms in a device, and the sequential charge deposition. PHITS can calculate the deposit energy random when a secondary particle crosses the sensitive volume of a device

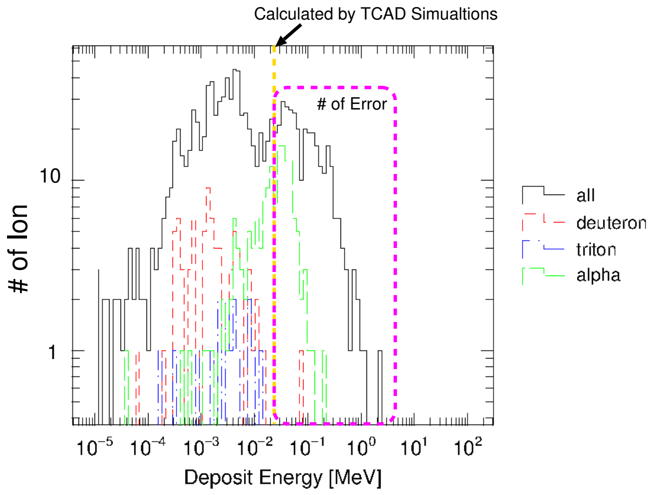


Fig. 2. The deposit energy by PHITS. The secondary particle, which deposit energy is larger than the threshold energy, is counted to one SEU.

as shown in Fig. 1. The deposit energy (E_{D}) corresponds to the particle's lost energy.

In the TCAD simulation part, generated charge (Q_{gen}) is collected into drain by a particle hit as shown in Fig. 1. An SEU (Single Event Upset) occurs in the circuit when Q_{gen} is large enough. We call it the threshold charge (Q_{th}), which is used to calculate the threshold deposit energy. Q_{deposit} can be converted to the E_{deposit}. E_{deposit} of 1 MeV is equivalent to Q_{deposit} of 50 fC[10].

Fig. 2 shows a relationship of the particle numbers and the deposit energy in the sensitive volume by PHITS simulations. The secondary particle, which deposit energy is larger than the threshold energy, is counted to one SEU. The numbers of those particles are considered to the numbers of SEUs. The deposit energy is calculated by TCAD simulations as shown in Fig. 2.

B. Simulation Setup

Fig. 3 shows a latch circuit and its layout structure. Fig. 4 shows the bird view of the device structure in PHITS simulations. It shows a latch structure. The red box indicates a sensitive volume. It is built based on the layout structures of the latch in test chips. The SOI body under the gate of an inverter is considered as a sensitive volume. The thicknesses of the thin BOX and the SOI body of SOTB are 10-nm and 12-nm while those are 25-nm and 7-nm in UTBB respectively. Alpha or neutron irradiation particles hit the latch model from above in PHITS. The same structures are constructed in TCAD simulations as 3D device-models as shown in Fig. 5. The 28-nm model is scaled by K rule from the 65-nm model. The particle hit the gate part of inverter in the latch..

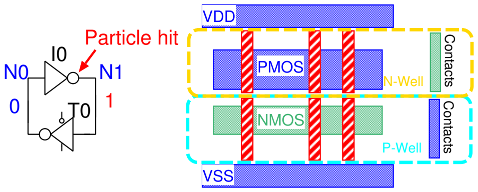


Fig. 3. A conventional latch and its layout structure.

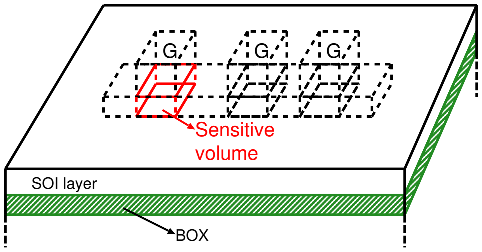


Fig. 4. Device structure used in PHITS simulations. This structure shows the sensitive volume of a latch. The SOI layers under G is regarded as the sensitive volume according to the TCAD simulation.

IV. Simulation and Experimental Results by Alpha Irradiation

We analyze the soft error rates of SOTB and UTBB structures according to supply voltages by the proposed simulation tool and alpha irradiation experiments. A 3MBq ^{241}AM alpha source is used in the experiments and the area of the alpha source is 1 cm^2 as shown in Fig. 6. The irradiation time is one minute.

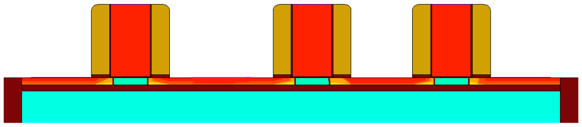
Eq. (1) is used to calculate cross-section by alpha irradiation.

$$CS_{\text{Alpha}}(\text{cm}^2/\text{bit}) = \frac{N_{\text{SEU}}}{F_{\text{Alpha}} \times N_{\text{bit}}} \tag{1}$$

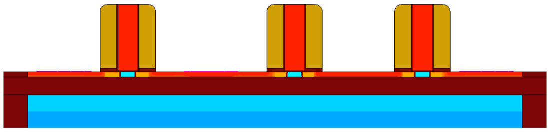
where N_{SEU} is the number of SEUs and F_{Alpha} is Flux of alpha particles. N_{bit} is the number of bits.

A. Simulation and experimental Results in SOTB Structure

Fig. 7(a) shows the alpha cross-section by the PHITS-TCAD simulations of the SOTB structure. VDD is decreased

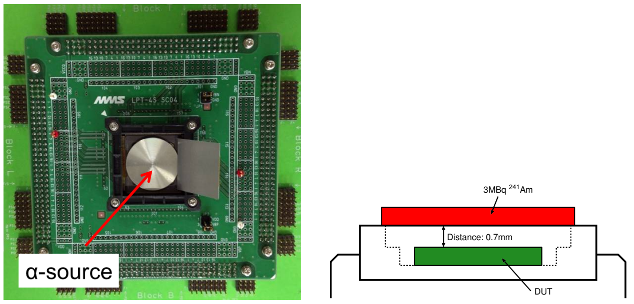


(a) The cross-section of 3D NMOS device model in the SOTB structure.



(b) The cross-section of 3D NMOS device model in the UTBB structure.

Fig. 5. The device-level models.



(a) Photo of the alpha source and chip.

(b) Image of the alpha experiments, the distance between alpha source and chip is 0.7 mm.

Fig. 6. Alpha experiment setup.

from 1.2 V to 0.4 V. The alpha irradiation experiments results are also shown in Fig. 7(a). In PHITS simulations, the numbers of the alpha particles are 10^8. The area of flip-flop is 4.08x1.8 μm^2. The number of FFs (one bit) in the test chip is 5x10^4. The cross-sections of SOTB latch increase by reducing the supply voltage. The cross-section increases 18x by decreasing the VDD from 1.2 V to 0.4 V according to the experimental results.

B. *Simulation and experimental Results in UTBB Structure*

Fig. 7(b) shows the alpha cross-section by the PHITS-TCAD simulations and experiments of the UTBB latch structure. There is no error in the UTBB structure when VDD is larger than 0.5 V according to the alpha irradiation experiments. Therefore, we sweep VDD form 0.45 V to 0.4 V in the simulations and experiments. The area of one flip-flop is 2.04x0.9 μm^2. The number of flip-flop in the test chip is 4x10^5. The cross-section increases 2.5x when VDD is reducing from 0.45 V to 0.4 V according to the experimental results.

The simulation results are 70% of the experimental results in average. It is because that the number of errors is very few according to the alpha irradiation experiments.

V. Neutron Irradiation Induced SERs by Simulations and Experiments

Fig. 8(a) and 8(b) show the neutron induced SER by neutron irradiation experiments and PHITS-TCAD simulations. The neutron irradiation experiments are conducted at RCNP in Osaka Univ. Eq. (2) is used to calculate the SERs of PHITS-TCAD simulations.

$$SER_{\mathrm{SBU}}[\mathrm{FIT/Mb}] = \frac{3.6 \times 10^{18} \times A_{\mathrm{neutron}} \times N_{\mathrm{SBU}} \times F}{N_{\mathrm{Neutron}}} \quad (2)$$

where A_{neutron} is the area of neutron beam in PHITS simulations. N_{SBU} is the number of SEUs and N_{Neutron} is number of all neutron particles.F is the Flux in the particle area.

According to the neutron irradiation experimental results, there is no error in the 28-nm UTBB structure. Thus, the SERs are shown by 90% error-bar in Fig. 8(b). The SERs increase by reducing the supply voltage. The SERs of UTBB are no larger than 15 FIT/Mb when the supply voltage is 0.4 V. The soft error tolerance of 28-nm UTBB is 10x stronger than the 65-nm SOTB when the supply voltage is 0.4 V according to the neutron irradiation simulations. The simulation results by PHITS-TCAD are consistent to the experimental results.

VI. Conclusion

We propose a PHITS-TCAD simulation tool to estimate the soft error rates according to supply voltages in 65-nm SOTB and 28-nm UTBB structures. It is easy to estimate the alpha and neutron induced soft error tolerance by this simulation tool by using the layout of test chip fabrication. The simulation time is shot. In the SOTB structure, the alpha cross-section increases 18x and neutron induced SERs increases 100x by reducing the supply voltage from 1.2 V to 0.4 V. In the UTBB structure, the soft error rates become much lower. There is no error occurrence in 28-nm UTBB according to the neutron experimental results. The 28-nm UTBB is 10x stronger than the 65-nm SOTB when the supply voltage is 0.4 V according to the PHITS-TCAD simulation results. The simulation results are consistent with the alpha and neutron irradiation experimental results.

REFERENCES

[1] D. Krueger, E. Francom, and J. Langsdorf, "Circuit design for voltage scaling and SER immunity on a quad-core itanium processor," in *ISSCC*, Feb. 2008, pp. 94–95.

[2] B. Olson, D. Ball, K. Warren, L. Massengill, N. Haddad, S. Doyle, and D. McMorrow, "Simultaneous single event charge sharing and parasitic bipolar conduction in a highly-scaled sram design," vol. 52, no. 6, pp. 2132–2136, Dec. 2005.

[3] N. Sugii, R. Tsuchiya, T. Ishigaki, Y. Morita, H. Yoshimoto, and S. Kimura, "Local $\mathrm{v_{th}}$ variability and scalability in Silicon-on-Thin-BOX (SOTB) CMOS with small random-dopant fluctuation," *IEEE Trans. Elec. Dev.*, vol. 57, no. 4, pp. 835 –845, Apr. 2010.

[4] P. Roche, J.-L. Autran, G. Gasiot, and D. Munteanu, "Technology downscaling worsening radiation effects in bulk: Soi to the rescue," in *IEDM*, Dec 2013, pp. 31.1.1–31.1.4.

[5] K. Kobayashi, K.and Kubota, M. Masuda, Y. Manzawa, J. Furuta, S. Kanda, and H. Onodera, "A Low-Power and Area-Efficient Radiation-Hard RedundantFlip-Flop, DICE ACFF, in a 65 nm Thin-BOX FD-SOI," *IEEE Trans. Nucl. Sci.*, vol. 61, no. 4, pp. 1881 – 1888, Aug. 2014.

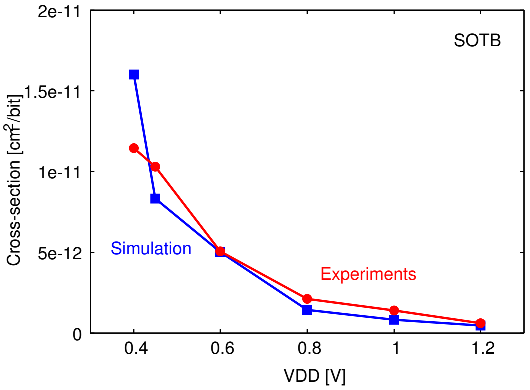
[6] K. M. Warren, B. D. Sierawski, R. A. Reed, R. A. Weller, C. Carmichael, A. Lesea, M. H. Mendenhall, P. E. Dodd, R. D. Schrimpf, L. W. Massengill, T. Hoang, H. Wan, J. L. D. Jong, R. Padovani, and J. J. Fabula, "Monte-Carlo Based On-Orbit Single Event Upset Rate Prediction for a Radiation Hardened by Design Latch," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2419 – 2425, Dec. 2007.

[7] K. Foley, N. Seifert, J. B. Velamala, W. G. Bennett, and S. Gupta., "Irt: A modeling system for single event upset analysis that captures charge sharing effects," in *Proc. Int. Rel. Phys. Symp.*, Jun. 2014, pp. 5F.1.1–5F.1.9.

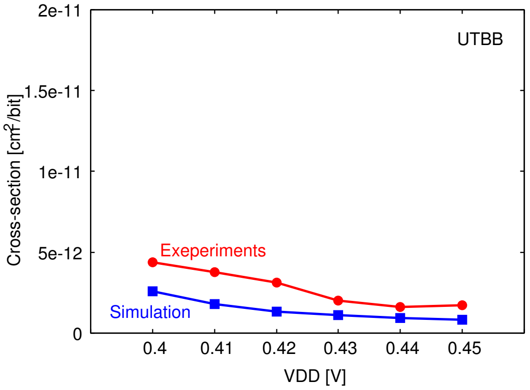
[8] S. Abe, R. Ogata, and Y. Watanabe, "Impact of Nuclear Reaction Models on Neutron-Induced Soft Error Rate Analysis," *IEEE Trans. Nucl. Sci.*, vol. 61, no. 4, pp. 1806–1812, Aug. 2014.

[9] K. Niita, N. Matsuda, Y. Iwamoto, H. Iwase, T. Sato, H. Nakashima, Y. Sakamoto, and L. Sihver, "Phits: Particle and heavy ion transport code system, version 2.23," in *JAEA-Data/code.*, no. 2010-022, 2010.

[10] T. Handa, K. Niita, and H. Sawamura, "Neutron-induced semiconductor soft error simulation using the phits monte carlo simulator," in *2003 symposium on nuclear data.*, 2003.

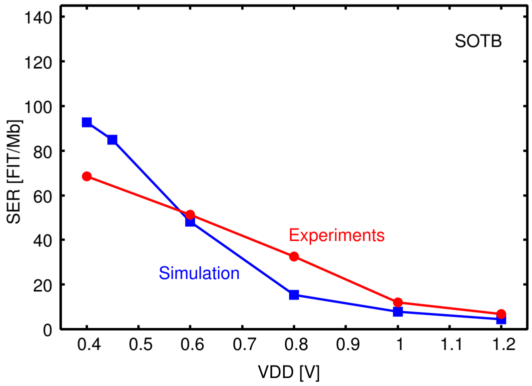


(a) The cross-section in SOTB structure according to the alpha irradiation experiments and simulations.

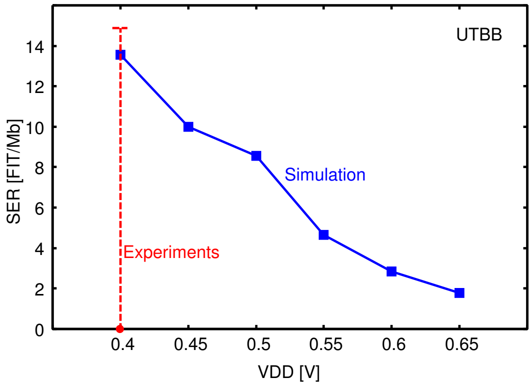


(b) The cross-section in UTBB structure according to the alpha irradiation experiments and simulations.

Fig. 7. Results of alpha irradiation experiments and PHITS-TCAD simulations.



(a) The SERs of SOTB structure according to the neutron irradiation experiments and simulations.



(b) The SERs of UTBB structure according to the neutron irradiation experiments and simulations.

Fig. 8. Results of neutron irradiation experiments and PHITS-TCAD simulations.