Anasysis of BOX Layer Thickness on SERs of 65 and 28nm FD-SOI Processes by a Monte-Carlo Based Simulation Tool

Kuiyuan Zhang, Shohei Kanda, Junki Yamaguchi, Jun Furuta and Kazutoshi Kobayashi
Graduate School of Science & Technology, Kyoto Institute of Technology

I. Abstract

We estimate the SERs of FD-SOI structures according to the thicknesses of BOX(Buird OXide) layer on 65-nm and 28-nm processes by reducing the supply voltage. Alpha, neutron irradiation experiments and Monte-Carlo based simulations are compared in this work. The SOTB(Silicon on Thin BOX) and UTBB(Ultra Thin Body and BOX) structures are used in the alpha and neutron irradiation experiments. The SERs of those structures 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. The parasitic bipolar effect is suppressed by thicker BOX on FD-SOI structure according to the simulation 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. Silicon On Thin BOX (SOTB)[2] and Ultra Thin Body and BOX (UTBB)[3] 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. Variations are suppressed due to the dopantless channel of FD-SOI. The supply voltage of SOTB can be decreased to 0.4 V[4]. Thus, It is necessary to investigate the soft error tolerance of FD-SOI structure at lower voltage.

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[5], IRT[6] and PHYSERD[7]. PHITS[8] 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 dates of layouts. As the simulation results are consistent to the experimental results, we make some new FD-SOI device-model by changing the thickness of BOX layer, and analyze the SERs of those models.

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. The simulation results of new device models are shown in section VI. Section VII 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 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 cross the sensitive volume of a device 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. E_{Deposit} can be converted to the Q_{deposit}. 1 MeV E_{deposit} is equivalent to 50 fC Q_{deposit}[9].

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 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. The same structures are constructed in TCAD simulations as 3D device-models.

IV. Alpha Irradiation Experimental and Simulation Results

We analyze the soft error rates of SOTB and UTBB structures according to supply voltages by the proposed simulations and alpha irradiation experiments. The simulation

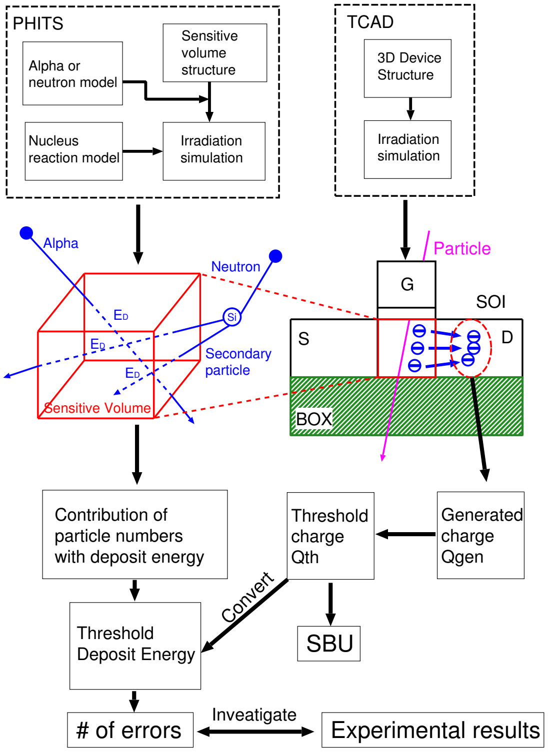


Fig. 1. Flow chart of the PHITS-TCAD simulation system.

results and experimental results are shown in this section. A 3MBq ^{241}AM alpha source is used in the experiments and the area of the alpha source is 1 cm^2. The irradiation time is one minute.

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

$$CS_{\text{Alpha}}(\text{cm}^2/\text{bit}) = \frac{N_{\text{error}}}{N_{\text{Alpha}} \times N_{\text{bit}}} \quad (1)$$

where N_{error} is the number of errors and N_{Alpha} is number of alpha particles. N_{bit} is the number of bits.

A. Simulation and experimental Results in SOTB Structure

Fig. 4(a) shows the alpha cross-section by the PHITS-TCAD simulations of the SOTB structure. VDD is decreased from 1.2 V to 0.4 V. The alpha irradiation experiments results are also shown in Fig. 4(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-section increases by reducing the VDD. It becomes easy to upset the SOTB latch 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. The PHITS-TCAD simulation results are consistent to the experiment results.

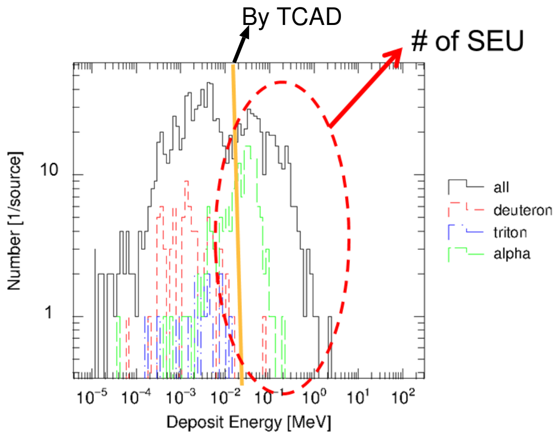


Fig. 2. The deposit energy by PHITS. The secondary particle, which deposit energy is larger than the threshold energy, is counted to one SEU.

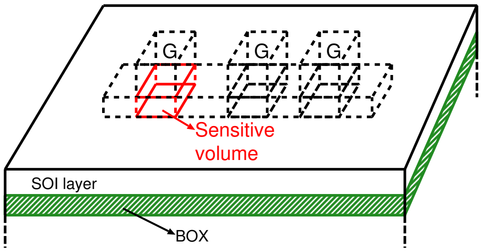


Fig. 3. Device structure used in PHITS simulations. This structure shows the sensitive volume of a latch. The SOI layers under G is regarded as the sensitive volume according to the TCAD simulation.

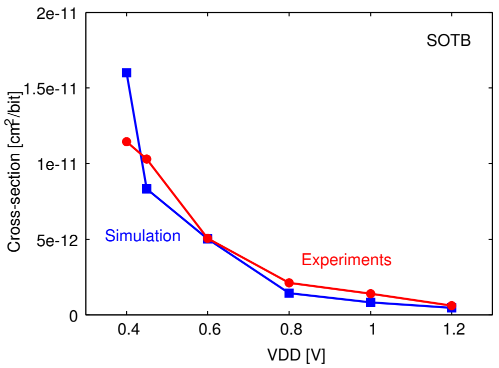
B. Simulation and experimental Results in UTBB Structure

Fig. 4(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 number of the alpha particles are 10^8 in the simulations. The area of one flip-flop is 2.04x0.9 μm^2. The number of flip-flop in the test chip is 4x10^5.

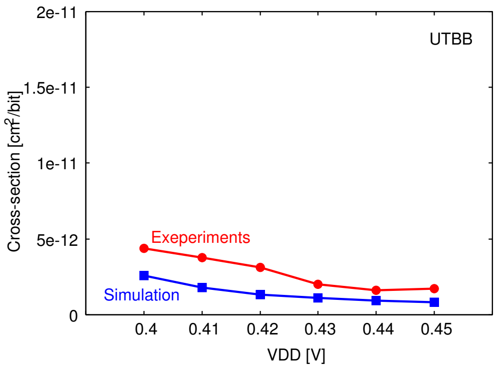
The cross-section also increases by reducing VDD. It increases 2.5x when VDD is reducing from 0.45 V to 0.4 V according to the experimental results. The simulation results are 70% of the experimental results in average. It is because that the number of errors is very few accroding to the alpha irradiation experiments. The cross-section of the UTBB structure is 1/15 of the SOTB structure when VDD is 0.4 V.

V. Neutron Irradiation Induced SERs by Experiments and Simulations

Fig. 5(a) and 5(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.

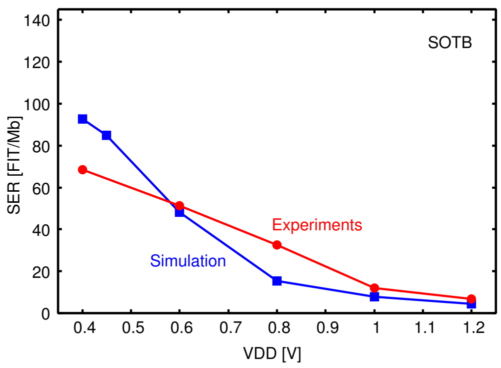


(a) The cross-section in SOTB structure according to the alpha irradiation experiments and simulations.

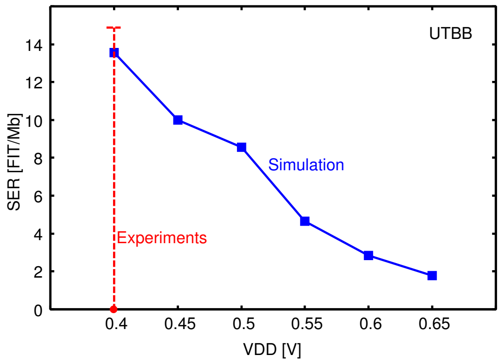


(b) The cross-section in UTBB structure according to the alpha irradiation experiments and simulations.

Fig. 4. 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. 5. Results of neutron irradiation experiments and PHITS-TCAD simulations.

$$SER_{\mathrm{SEU}}[\mathrm{FIT/Mb}] = \frac{3.6\times10^{18}\times A_{\mathrm{neutron}}\times N_{\mathrm{SBU}}\times F}{N_{\mathrm{neutron}}} \qquad (2)$$

where $\mathrm{A}_{\mathrm{neutron}}$ is the area of neutron beam in PHITS simulations. $\mathrm{N}_{\mathrm{SBU}}$ is the number of SEUs and $\mathrm{N}_{\mathrm{Neutron}}$ is number of all neutron particles. F is the Flux as the same as RCNP.

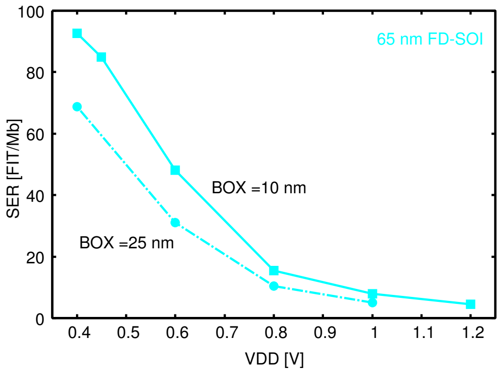
Accroding to the neutron irradition experimental results, there is no error in the 28-nm UTBB structure. Thus, the SERs are shown by error-bar in Fig. 5(b). The SER is no larger than 15 FIT/Mb when VDD is 0.4 V. The 28-nm UTBB is 10x stronger than the 65-nm SOTB when VDD is 0.4 V according to the neutron irradiation simulations. The simulation results are consistent with the neutron irradiation experimental results.

VI. Neutron induced SERs on 65 and 28-nm processes influenced by BOX layer Thicknesses

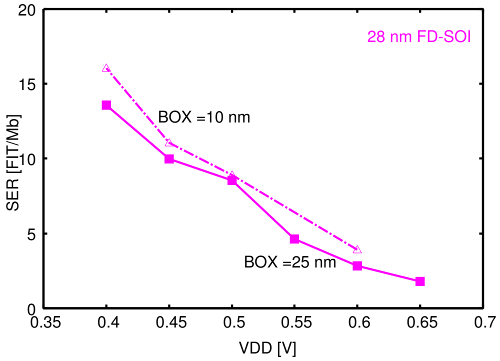
As the results of simulations are consistent to the experimental results, The SERs of several device models can be forecast. In this section, we change the thickness of BOX layer in the 65-nm SOTB and 28-nm UTBB by TCAD simulations. The thicknesses of BOX layer and SOI body in 65-nm FD-SOI are 25-nm and 10-nm while those are 10-nm and 7-nm in 28-nm FD-SOI respectively. The SERs of these new models are analyzed by the PHITS-TCAD simulation tool influenced by reducing the supply voltage.

Fig. 6 shows the neutron irradiation simulation results by PHITS-TCAD. In the 65-nm FD-SOI structure, the collected charge reduces by a particle hit. The main mechanism of charge collection in FD-SOI is parasitic bipolar effect. The substrate voltage is increased when the bipolar is turned on by a particle hit. However, it affect the SOI layer weakly by increasing the thickness of BOX. The SERs of 65-nm decrease almost 20% as shown in Fig. 6(a). Against to the 65-nm process, the bipolar effect becomes weaker when supply voltage is lower than 0.6 V. The SERs of 28-nm only increase 10% by thinner BOX layer as shown in Fig. 6(b).

Fig. 7 shows the threshold LET influenced by the thickness of BOX in the 65-nm FD-SOI structure according to the TCAD simulations. The threshold LET decreases by thinner BOX layer. The parasitic bipolar effect of substrate is suppressed by the thicker BOX. Fig. 8 shows the potential of substrate after the particle hit by TCAD simulations. The potential of BOX keeps low when the thickness of BOX is 100 nm. The voltage of SOI layer is hard to increase. The soft error tolerance become stronger when the thickness of BOX is increased.



(a) Simulation results of 65-nm FD-SOI. The SERs decrease by thicker BOX layer.



(b) Simulation results of 28-nm FD-SOI. The SERs increase by thinner BOX layer.

Fig. 6. Results of neutron irradiation simulations by PHITS-TCAD simulations. The thicknesses of BOX layer are changed.

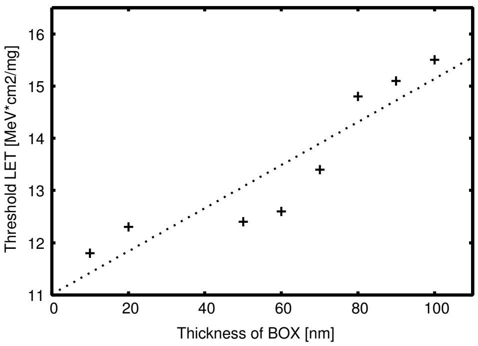
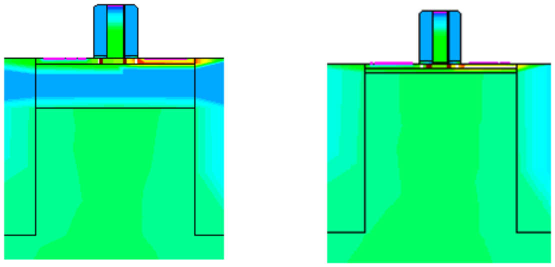


Fig. 7. The threshold LET influenced by the thickness of BOX in 65-nm FD-SOI. The supply voltage is 1.0 V.



(a) The thickness of BOX is 100 nm. The potential of BOX layer keeps low. The bipolar effect is suppressed by thicker BOX.

(b) The thickness of BOX is 10 nm. The potential of BOX layer increases. The bipolar effect affect the BOX and SOI layers.

Fig. 8. The situation of substrate potential after the particle hit.

VII. Conclusion

We analyze the alpha particle and neutron induced SERs by irradiation experiments and monte-carlo based simulation tool PHITS-TCAD. The 65-nm SOTB and 28-nm UTBB structures are used in our estimation. In the SOTB structure, the alpha cross section increases 18x by reducing the supply voltage from 1.2 V to 0.4 V. In the UTBB structure, the alpha cross section increases 2.5x by reducing the supply voltage from 0.45 V to 0.4 V. The SERs of the 28-nm UTBB is 1/15 of the 65-nm SOTB when VDD is 0.4 V. There is no error occurrence in 28-nm UTBB according to the neutron experimental results. The simulation results are also consistent with the neutron irradiation experimental results.

According to the PHITS-TCAD simulation results, the SERs of 65-nm FD-SOI structure are 20% decreased when the BOX layer are increased from 10nm to 25nm. However, the SERs of 28-nm FD-SOI only increase 10% when the BOX layer are decreased to 10nm. The parasitic bipoar effect is suppressed by thicker BOX layer.

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] 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.

[3] 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.

[4] K. Kobayashi, K. 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.

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] 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.