Analysis of Soft Error Rates by Supply Voltage in 65-nm SOTB and 28-nm UTBB Structures by a PHITS-TCAD Simulation System

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Abstract— **We analyze the soft error tolerance of a latch in 65-nm SOTB (Silicon on Thin BOX) and 28-nm UTBB (Ultra Thin Body and BOX) processes by a PHITS-TCAD simulation system. The proposed system is composed of two parts, the device-simulation and the physics simulation by PHITS (Particle and Heavy Ion Transport code System). The alpha and neutron induced soft error rate can be analyzed without test chip and experiment. We investigate the soft error tolerance on 65-nm SOTB and 28-nm UTBB by simulations and experiments. The simulation results are consistent with the experiment results.**

I. 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 paper, we analyze the alpha particle and neutron induced soft errors on 65-nm SOTB and 28-nm UTBB latch by a PHITS[6]-TCAD simulation system and alpha experiments. There is only heavy ion model in TCAD simulator. The alpha particle and neutron induced soft error tolerance can be analyzed by PHITS. The proposed simulation system is similar to PHYSERD[7], while the simulation time is much shorter than PHYSERD. 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 15x stronger than 65-nm SOTB when VDD 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. The simulation results are consistent with alpha irradiation experimental results.

II. PHITS-TCAD SIMULATION SYSTEM

Fig. 1 portrays a flow chart of our simulation system by PHITS and TCAD. PHITS 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 when a secondary particle cross the sensitive volume of a device as shown in Fig. 1. The deposited energy ($\mathrm{E_D}$) 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 SBU 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. Note that the threshold charge (Q_{th}), which collected by drift and diffusion only, is different from critical charge (Q_{crit}). E_{D} can be convert to the Q_{deposit}. 1 MeV E_{deposit} is equivalent to 50 fC Q_{deposit}[8] in this research.

A list of particle numbers with deposit energy is also obtained by PHITS. The secondary particle, which deposit energy is larger than the threshold deposit energy, causes one SBU. According to the particle list, the total numbers of the secondary particles are equal to the number of SBUs.

Fig. 2 shows the simulation times of PHITS-TCAD simulation system and PHYSERD according to the number of secondary ions. We assume one TCAD simulation cost two hours and one PHITS simulation cost one hour average. It takes 10 times TCAD-simulation to calculate the Q_{th}, and one time PHITS-simulation to calculate the number of SBUs. Thus, the simulation time is about 21 hours. It does not increase by the number and SBUs. However, It has to do one time PHITS-simulation and N times TCAD-simulations (where N is the number of SBUs) by PHYSERD. Thus, It takes $2N$+1 hours to get the simulation results.

III. SIMULATION SETUP

Fig. 3 shows a conventional latch schematic and layout. A radiation particle hits the gate of the NMOS transistor of the inverter I0. Well contacts are placed side by side in the same rows. The nodes N1 is set to "1". The thickness 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. A ion particle hits the gates of inverter in the SOTB and UTBB. The minimum LET of ion which upsets the latches is threshold LET.

Fig. 4 shows the image of the device structure in PHITS simulations. It shows a latch structure in a flip-flop size. The red box indicates a sensitive volume. It is built based on the layout structures of the latch. The SOI body under the gate of an inverter is considered as a sensitive volume.

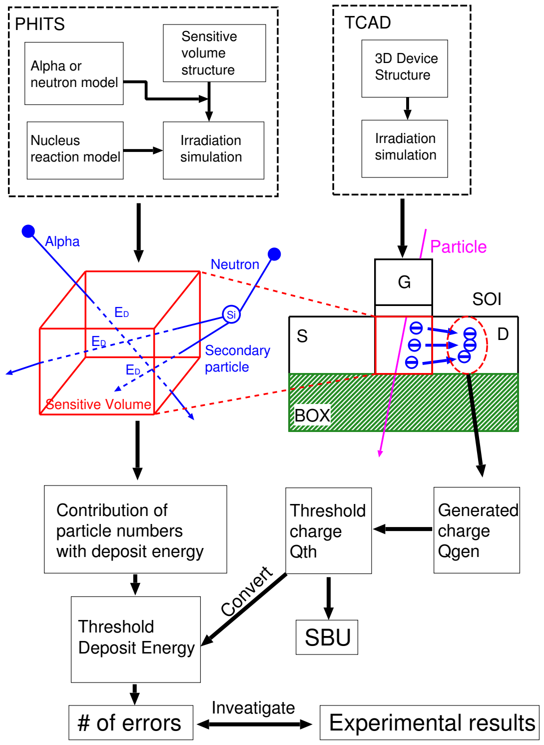


Fig. 1. Flow chart of the PHITS-TCAD simulation system.

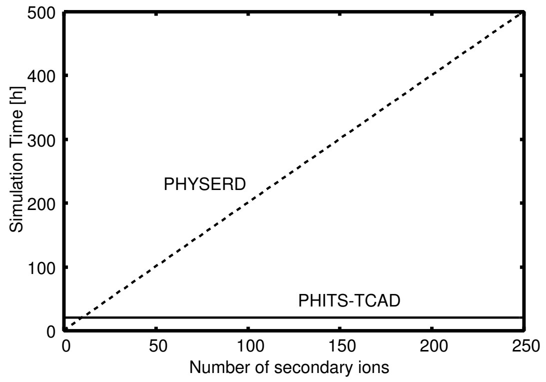


Fig. 2. Comparison of the simulation time of PHITS-TCAD and PHYSERD.

Therefore, the volume of the sensitive area in UTBB and SOTB structure is 30 nm×200 nm×7 nm and 70 nm×400 nm×12 nm respectively.

IV. SIMULATION AND ALPHA EXPERIMENT 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 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.

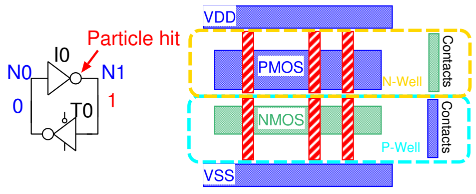


Fig. 3. A conventional latch and its layout structure.

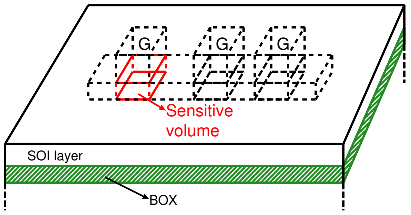


Fig. 4. Device structure used in PHITS simulations. This structure shows the sensitive volume of a latch. The SOI layers under G is regarded as the sensitive volume according to the TCAD simulation.

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

where N$_{\text{error}}$ is the number of errors and N$_{\text{Alpha}}$ is number of alpha particles. N$_{\text{Alpha}}$ is the number of bits.

A. Q_{th} Calculation for PHITS simulation

PHITS is a multi-scale Monte Carlo simulator by linking a particle transport code. Thus, it does not consider the parasitic bipolar effect as in the TCAD simulation. The generated charge in the sensitive volume only by drift and diffusion is used as the Q_{th} for PHITS simulations.

Fig. 5 shows the two current waveforms when a threshold LET ion particle hits the SOI latch by TCAD simulation. The blue curve is the current pulse by electrons, while the red one occurs by holes. The electrons are collected into drain by drift and diffusion and the parasitic bipolar effect when a high energy particle hit device. The collected charge which is same as the holes are collected only by drift and diffusion. We integrate the current curve collected by drift and diffusion to calculate the Q_{th}.

B. Simulation Results in SOTB Structure

Fig. 6(a) shows the alpha cross-section by the PHITS-TCAD simulations of the SOTB structure. VDD is changed from 1.2 V to 0.4 V. The alpha irradiation experiments results are also shown in Fig. 6(a). The number of the alpha particles are 10^8 in the simulations. The area of flip-flop is 4.08x1.8x10^{-8} cm^2. The number of flip-flops 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.

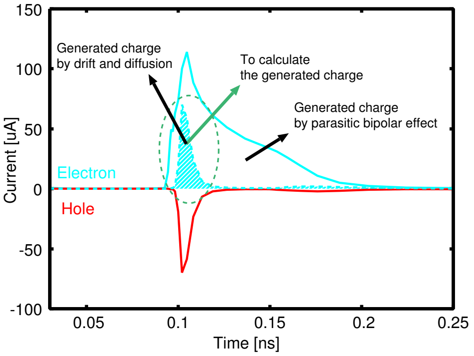


Fig. 5. Current waveform by a particle hit. Blue current pulse is generated by electron collection, while the red is by hole collection. The generated charge collected by drift and diffusion is used to calculate the Q_{th}.

C. Simulation Results in UTBB Structure

Fig. 6(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 flip-flop is 2.04x0.9x10^{-8} cm^2. The number of flip-flop in the test chip is 4x10^5.

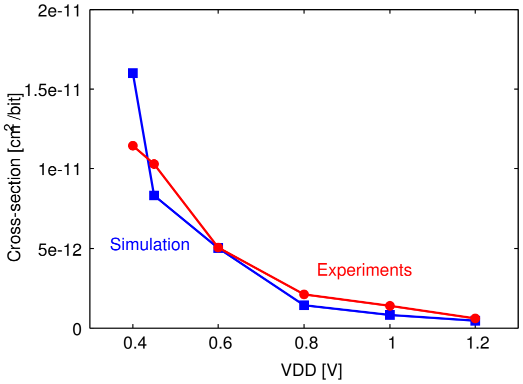
The cross-section also increases by reducing VDD. It increases 2.5x when VDD is reducing from 0.45 V to 0.4 V according to the experimental results. The simulation result is 70% of the experimental result. It is because that There is only little number of soft errors in the UTBB structure. The sensitive volumn of UTBB is so small. There is only little charge generation in UTBB. Furthermore, the probability of particles hit transistors are decreased by scaling. It also make UTBB become stronger to soft error. The cross-section of the SOTB structure is 15x more than the UTBB structure when VDD is 0.4 V.

V. Neutron Irradiation Induced SER by Simulations and Experiments

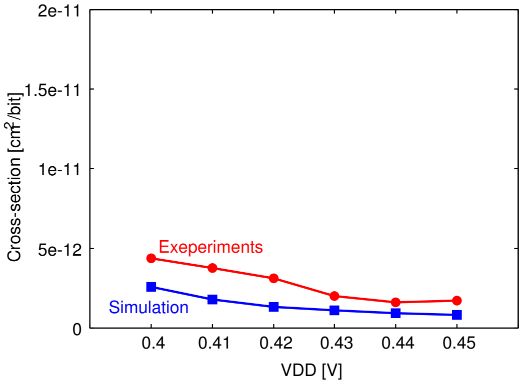
Fig. 7(a) and 7(b) show the Neutron induced SER by PHITS-TCAD simulations and neutron irradiation experiments. The neutron irradiation experiments are conducted at RCNP in Osaka Univ. Eq. (3) is used to calculate the SERs of neutron irradiation simulations.

$$SER_{\mathrm{SBU}} = 3600 \times 10^9 \times A_{\mathrm{neutron}} \times N_{\mathrm{SBU}}/N_{\mathrm{Neutron}} \quad (2)$$

$$\times F \times 10^6[\mathrm{FIT/Mb}] \quad (3)$$



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



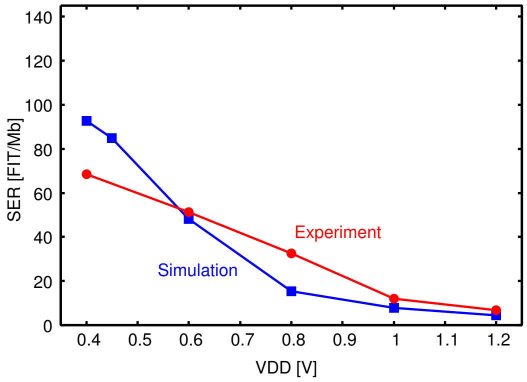
(b) The cross-section in UTBB structure according to the alpha irradiation experiments and simulations.

Fig. 6. Results of alpha irradiation experiments and PHITS-TCAD simulations.

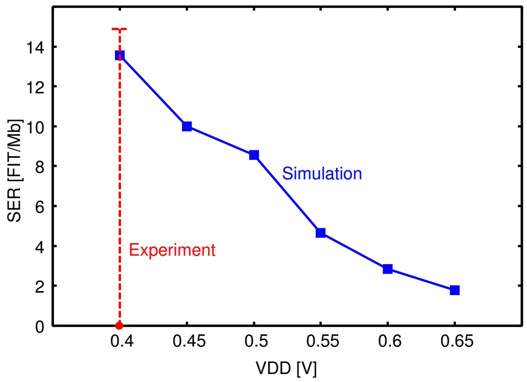
where $\mathrm{A}_{\mathrm{neutron}}$ is the area of neutron beam in PHITS simulations. $\mathrm{N}_{\mathrm{SBU}}$ is the number of SBUs and $\mathrm{N}_{\mathrm{Neutron}}$ is number of neutron particles. F is Flux. These parameters are all set by PHITS. There is no error in the 28-nm UTBB structure by experimental results. The SERs are shown by error-bar in Fig. 7(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. CONCLUSION

We propose a PHITS-TCAD simulation system to estimate the soft error rates according to supply voltages in 65-nm SOTB and 28-nm UTBB latch structures. It is easy to estimate the alpha and neutron induced soft error tolerance by this simulation system without chip fabrication. It only takes 20 hours to finish all simulations by PHITS-TCAD, while takes more than 500 hours to finish one simulation by PHYSERD. The simulation time is much shorter than other simulation systems. In the SOTB structure, the alpha cross-section increases 18x by reducing the VDD to from 1.2 V to 0.4 V. In the UTBB structure, the cross-section increases 2.5x by reducing the VDD from 0.45 V to 0.4 V. The soft error tolerance of the 28-nm UTBB is 15x stronger than 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 28-nm UTBB is 10x stronger than the 65-nm SOTB when VDD is 0.4 V according to the PHITS-TCAD simulation results. The simulation results are also consistent with the neutron irradiation experimental results.



(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. 7. Results of neutron irradiation experiments and PHITS-TCAD simulations.

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