Neutron radiation prediction model based on Geant4 Simulation

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Abstract. As SRAM is scaled down to a smaller size, it will induce multi-bit upset(MBU) when incident neutron react with silicon material. Based on Geant4, compound sensitive volume and multi-sensitive volume model are constructed to predict single-bit upset (SEU) and MBU caused by the single event effect of neutron. The prediction of SRAM upset of 40nm bulk silicon technology is carried out with this model. The results show that the prediction results in this paper are in good agreement with the actual test results, which proves the accuracy of the model.

1. Introduction

In the space environment, the operation of the components will be affected by the radiation environment. Pickel and Blandford[1] confirm that these anomalies are caused by single event effect. Therefore, it is significant to study the single event effects of space particles (such as neutrons). The phenomenon has been confirmed by several studies at the avionics heights and near-ground altitudes [2] [3].CERN developed Geant4 software [4], which is an effective tool to predict single event effects.

In the last ten years, as the technology scales, the sensitivity of the device to the single particle effect caused by the incident neutron is also changed[5].On the one hand, the decrease of working voltage and the increase of working frequency lead to the decrease of threshold charge in SRAM memory cell and the increase of sensitivity to single event effect. On the other hand, the reduction of the technology node leads to the decrease of the distance between the sensitive elements and increases the possibility of MBU in the device. Therefore, the need to study the single event effect of neutron, especially the MBU, is shown. Most of the articles are the research on the SEU, and most studies on MBU are based on the ground radiation experiment. There are fewer prediction model of MBU.

Aiming at the neutron radiation, this paper proposes a compound sensitive volume model based on Geant4 for single-bit upset prediction. Furthermore, a multi-sensitive volume model is established for multi-bit upset prediction. Finally, the SEU and MBU predictions of neutron radiation are carried out respectively, and the results are compared with the literature.

2. establishment of the compound sensitive volume

2.1 Choice of Geant4 physical model

Geant4 is a three-dimensional Monte Carlo simulation toolkit,It is used for the transmission of basic particles from heat energy (neutron) to PeV energy, which is the result of the cooperation of 100 scientists from more than 40 research institutes from all over the world[6].

Geant4 provides 7 physical processes to describe the interaction between particles and matter, The selection of different physical processes has different effects on the results of Monte Carlo simulation. It is mainly reflected in the number of secondary particles produced.This paper use the standard physical process package FTFP_BERT_HP, which contains model and cross section data of different physical processes about neutron, proton and other particles.

2.2 Establishment of Geant4 compound sensitive volume

Based on the simulation work on the TCAD software, this paper get the compound sensitive volume's three dimensional parameter data,it is shown in Table 1.The threshold LET of 40nm NMOS device is 0.18 Mev·cm^2/mg. This paper starts the neutron radiation simulation with Geant4 software.

By the simulation of heavy ion radiation, the σ-LET curves of heavy ions are obtained statistically. Then the correlation parameters obtained by Weibull function are compared with those of literatures, so as to modify the compound sensitive volume model.

Table 1. Compound sensitivity volume parameters

Sensitive volume	α	W（μm）	L（μm）	D（μm）	Qcollected（fC）
SV1	1	0.16	0.16	0.15	10.2
SV2	0.79	0.68	0.68	0.9	8.14
SV3	0.72	1.24	1.24	2.0	7.32

2.3 Heavy ion radiation simulation

The neutron itself is not charged. Therefore, the single event effect of neutrons mainly depends on the reaction with target materials to produce secondary particles, and then secondary energy is indirectly ionized by secondary particles,and then indirectly ionized to deposit energy thorough secondary particels. Therefore, the relevant parameters of the sensitive body model can be corrected by the simulation of heavy ion radiation.

Table 2. Heavy ion parameter data

Particle	Energy（MeV）	Range（μm）	LET（MeV·cm^2/mg）
^{11}B	200	899.48	0.539
^{14}N	170	294.46	1.484
^{20}Ne	110	69.01	5.145
^{31}P	150	51.29	10.51
^{52}Cr	250	46.81	22.1
^{58}Ni	265	43.79	28

In order to get the σ-LET curve,it is requisite to select suitable heavy ions with different energy and different LET values to carry out the radiation experiment. This paper completes the work through SRIM software. The information of type and energy of incoming ions can be set up at the software interface, and the range and LET value of the ion in target material can be obtained by setting different kinds of target materials.The selected heavy ion data is shown in Table 2.

As can be seen from Table 2, with the increase of Z, the range of heavy ions decreases and the LET value increases. The radiation experiments were carried out with the heavy ions mentioned above, and the corresponding heavy ion upset cross sections were calculated. The experimental results were fitted with Weibull function,which is showed as follews:

$$\sigma(\text{LET}) = \sigma_{sat}\{1 - e^{-[\frac{LET-LET_{th}}{W}]^s}\}, LET \geq LET_{th} \qquad (1)$$

In which σ is upset cross section,σ_{sat} is the saturated upset cross section,LET_{th} represents the threshold LET,W,S are the parameters of the Weibull function. Figure 1 is the Weibull fitting curve of the results of the heavy ion radiation experiment of the 40nm technology node. The fitting parameters are as follows:σ_{sat}=9.65e-10cm^2,LET_{th}=0.185478Mev·cm^2/mg,w=6.5944e7,s=0.21569,R^2=0.9386.R^2 reflects the degree of fitting, which shows that the fitting effect of this Weibull is good.The value of saturated cross section and the value of saturated cross section of literature [4],which is tested in the heavy ion radiation experiment of Xilinx 45-nm Spartan-6 XC6SLX16 FPGA, is in line with the order of magnitude,and the error is about 3.5%.Moreover,the LET threshold is also very close to the LET threshold obtained from TCAD simulation,the error is about 3%.It indicates that the Geant4 simulation model established in this paper is reasonable, and it lays the foundation for the later multi sensitive volume experiment.
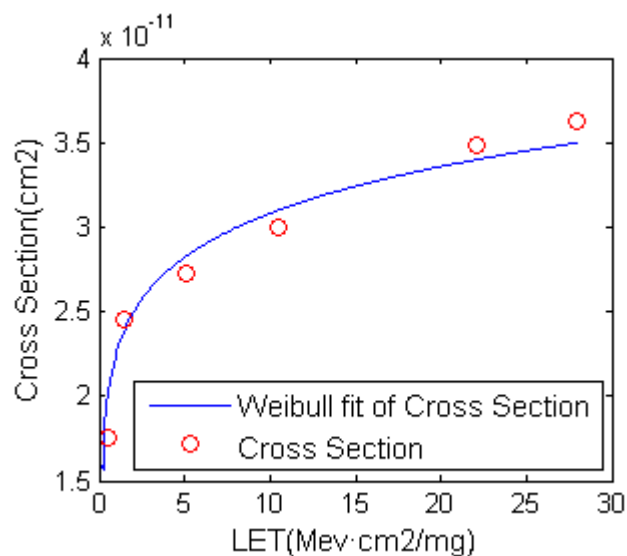

Figure 1. Weibull fitting of heavy ion upset cross section.

3. Upset prediction of neutron based on Geant4

3.1 Upset prediction of SEU
Based on the model of Geant4 compound sensitive volume established in the second section, the SEU upset prediction is carried out for the 40nm technology.

The neutrons with the energy of 2-10MeV and 10-150 MeV are simulated. The 45nm SRAM data: Density=128Mbit, Qcrit=0.4fc[8], as shown in Figure 2.
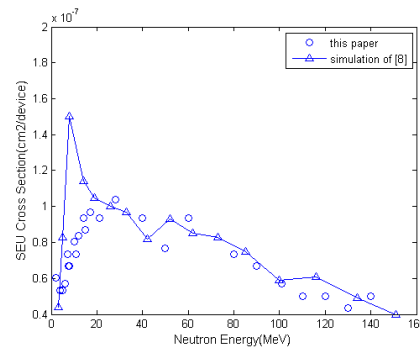
Figure 2. SEU cross section of this paper
and the literature [8].

As we can see from Figure 2, when the neutron energy is above 15MeV, the agreement between this paper and the literature [8] on the value and change of the SEU cross section is very high. When the neutron energy is below 15MeV, the change of the SEU cross section is basically the same, but the position of the peak value is different, the peak value is about 35% smaller than the peak value of the literature [8].

The method in [8] is based on the Monte Carlo CORIMS software. Eishi points out that with the increase of energy, there will be a shape peak in the cross section below 10MeV, which is mainly the contribution of lighter particles. The above differences, which is mainly caused by light particles, may be due to the different nuclear reaction data contained in the physical process of CORIMS and Geant4. Therefore, there is little difference between simulation results in the interval of high-energy neutron.

3.2 Upset prediction of MBU
Based on the neutron radiation model verified in the previous section, nine identical compound sensitive volumes ,which is in accordance with the actual distance of the SRAM device,are built in this section so as to study the characteristics of MBU of neutron radiation in 40nm technology. It is shown in Figure 3.When the energy of the secondary particle reaches a certain value, it will pass through a number of sensitive bodies and deposit energy on the track. If the energy deposited in more than 2 sensitive bodies exceeds the threshold energy, the MBU is detected.
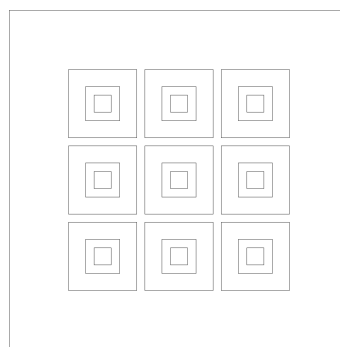

Figure 3. Section of the Multi sensitive
volume prediction model

This paper mainly measures the neutron induced multi bit upset with the energy below 20Mev , and calculates the proportion of SEU and MBU generated by neutron radiation of different energy.The probability of MBU indicates the probability that multiple sensitive volume will upset in one event. the formula[9] is as follows:

$$MBU_{prob} = \frac{Evt_{MBU}}{Evt_{MBU} + Evt_{SBU}} \tag{2}$$

Where Evt_{MBU} says the number of MBU event,Evt_{SBU} says the number of MBU event.Moreover,2-bit upset, 3-bit upset, 4-bit upset and 5-bit upset are calculated respectively.

Figure 4 shows the results of multiple sensitive volume simulations with energy below 20 Mev, starting with energy of 2 Mev and performing a neutron radiation experiment every 2 Mev.It calculates the proportion of multi-bit upset through formula (2) and obtains the ratio of SEU.It can be seen that only SEU occurs at the energy of 2 Mev due to the low energy of the incident neutrons. Therefore,the primary energy of the secondary ions produced by the reaction of the neutron with the Si target is low and the deposited energy collected on the track by the sensitive volume is not enough to cause MBU.A 2-bit upset occurs when 4 Mev neutrons radiates, a 3-bit upset occurs when 6 Mev neutrons radiates, a 4-bit upset occurs when 8 Mev neutrons radiates, and a 5-bit upset occurs when 18 Mev neutrons radiates, though Its proportion is very low.
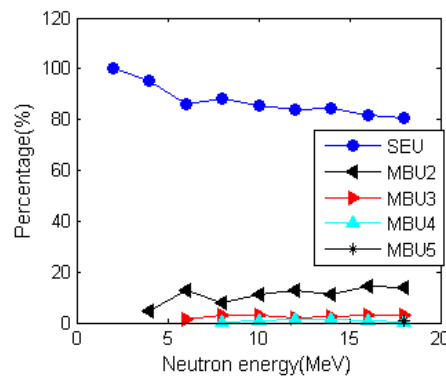

Figure.4 The upset proportion of neutron radiation
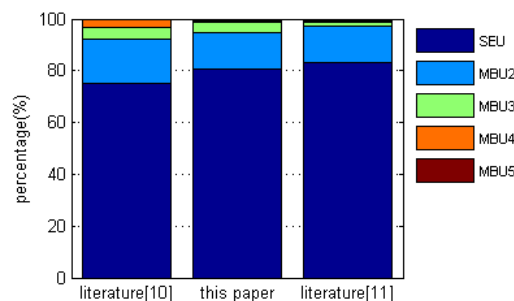with different energy

Figure.5 Comparison of upset multiplicity

Tncident neutron with the energy of 18Mev are selected: SEU is 80.8%, MBU2 is 14%, MBU3 is 4%, MBU4 is 0.4% and MBU5 is 0.8%. The selected data are compared with the data measured by 40 nm SRAM at Laboratoire Leon Brillouin (LLB) in [7] and the simulation data by TIARA / Geant4 code in [8].Figure 4 depicts the proportion of upset multiplicity between this paper and [7] and [8].

Figure 5 depicts the ratio of the upset multiplicity. The total ratio of MBU in this paper is close to the measured values in [10]. The difference between MBU2 and MBU3 is small, and the difference is mainly on MBU4 and MBU5.The ratio of MBU in this paper is about 5.8% smaller than that of [10]. Compared with the simulation results of [11], the ratio of MBU2, MBU4 and MBU5 is very close, and the total ratio difference of MBU is reflected on MBU3.

From the comparative analysis of upset multiplicity above, it can be seen that the difference between the prediction model of multi sensitive body and the measured value is mainly reflected in MBU4 and MBU5, which is consistent with the Geant4 simulation results of Autran. As a whole, the maximum error is not more than 6%, indicating that our MBU prediction model is feasible.

4. Conclusion

Based on Monte Carlo Geant4 software, a prediction model of compound sensitive volume is built to predict SEU and MBU caused by neutron single event effect, and is verified for 40nm technology of bulk silicon. The main work is as follows:

- Simulation of heavy ion radiation. The saturated cross section of heavy ion is 9.65e-10cm^2, and the error is 3.5% compared with the literature. It shows that the parameters of the prediction model of the compound sensitive volume are reasonable.
- Prediction of SEU and MBU for 40nm technology.The result of prediction is in good record with the test result,which shows that the upset prediction model proposed in this paper is feasible.

    The prediction model proposed in this paper is not only suitable for 40nm process, but also can be used to predict the neutron radiation in other technology by modifying and verifying the model of the compound sensitive volume.

References

[1]   Pickel J C and Blandford J T 1978 Cosmic Ray Induced in MOS Memory Cells *on Nuclear Science, IEEE Transactions*. **25** 1166-1171.
[2]   Ziegler J F 1996 J. *Ibm Journal of Research & Development*.**40** 19-40.
[3]   Normand E 1996 *on Nuclear Science, IEEE Transactions*. **43** 2742–2750.
[4]   C Inguimbert, Duzellier S and Ecoffet R 2002 *on Nuclear Science, IEEE Transactions*.**49** 1480–1485.
[5]   Merelle T, Saigne F, Sagnes B, et al 2005 J.**3** 1-6.
[6]   Geant4-CERN ENDF/B-VII Incident-Neutron Data:http://t2.lanl.gov/nis/data/endf/endfvii-n.html
[7]   Gadlage M J, Roach A H, Duncan A R, et al. 2015 *Nuclear Science,IEEE*.**62** 2717-2724.
[8]   Ibe E, Taniguchi H, Yahagi Y, et al. 2010 J. *IEEE Transactions on Electron Devices*.**57** 1527-1538.
[9]   Tipton, A. D., Zhu, X., Weng, H., Pellish, J. A., Fleming, P. R., & Schrimpf, R. D., et al 2008 *IEEE Transactions on Device & Materials Reliability*.**8** 565-570.
[10]   Laboratoire CEA-CNRS Léon Brillouin (LLB) [Online]. Available:http://www-llb.cea.fr
[11]   Autran J L, Serre S, Semikh S, Munteanu D, Gasiot G,and Roche P 2017 *IEEE Transactions on Nuclear Science* **59** 2658-2665.