第 32 卷 第 1 期 原 子 核 物 理 评 论 Vol. 32, No. 1
2015 年 3 月 Nuclear Physics Review Mar., 2015

Article ID: 1007-4627(2015) 01-0100-05

Impact of Heavy-ion Nuclear Reactions on Single Event Upset

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Abstract: This work investigates the effect of nuclear reactions resulting from the interaction of heavy-ion with the specific devices on single event upset (SEU), since the traditional application of linear energy transfer (LET) as an engineering metric may be unsatisfied on SEU characterization or has no ability to directly present the property of nuclear reaction (including its probability and secondary ions). Using Monte Carlo simulation and in-depth analysis, this study provides a powerful comparison between direct ionization processes and the one within nuclear reactions. The different heavy ions have been applied in simulation to characterize the role of nuclear reactions in SEU occurrence. The results show that the contribution of heavy-ion nuclear reactions to SEU cross section depends on ion energy with a non-monotonic relationship. Based on the simulated results, suggestions were put forward that the worst case of SEU occurrence induced by heavy-ion nuclear reactions should be considered to predict the on-orbit SEU rate.

Key words: single event upset; linear energy transfer; nuclear reaction; heavy ion
CLC number: TN386.1 **Document code:** A **DOI:** 10.11804/NuclPhysRev.32.01.100

1 Introduction

Heavy-ion test based on the ground accelerator as an effective method is often used to investigate single event upset (SEU) in modern integrated circuits[1−6]. Generally, linear energy transfer (LET) of heavy ions has been considered as an engineering metric to study the SEU occurrence of electronic devices. The SEU cross section measured by heavy ions is often described by ion LET with a Weibull function[7−8]. Based on the model of space radiation environment, the total on-orbit SEU rate is approximately estimated using the Weibull curve fitted by the ground experimental data[1,3]. However, many studies revealed that the use of LET in ground heavy-ion test where the nuclear reactions dominate the SEU occurrence is not sufficient to describe the SEU data[8−14]. For example, Dodd *et al.* presented that the curves of SEU cross section versus LET for low and high energy heavy ions exhibit a significant difference below the threshold LET of direct ionization induced upset[14]. Other studies have shown that the SEU occurrence arising from heavy-ion nuclear reaction relies on ion energy and species, respectively[8,10−11]. Additionally, Reed *et al*[12]. suggested that the ground heavy-ion test should be carried out by several types of ions of different energies when heavy-ion nuclear reactions are a contributing factor for the event rate of devices. Up to now, little work has been done to study the specific relationship between the nuclear reaction induced SEU cross section and ion energy (or species), which is crucial to the accurate characterization of SEU in ground heavy-ion test.

In this paper, the SEU occurrence induced by heavy-ion nuclear reaction has been studied by Monte Carlo simulation. The influence of heavy-ion energy and species on SEU cross section induced by nuclear reactions was systematically investigated. Finally, for the prediction of on-orbit SEU rate, the existing risks from heavy-ion nuclear reactions were discussed.

2 Simulation details

The Cosmic Ray Effects on Microelectronics Code Monte Carlo (CRÈME-MC) software package[15−17], which is a computational tool based on Geant4 li-

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Received date: 5 Mar. 2014; **Revised date:** 18 Apr. 2014
Foundation item: National Natural Science Foundation of China(11179003, 10975164, 10805062 11005134)

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braries, was used to evaluate the rate of SEEs. In this package, physical processes such as ionization, nuclear elastic, nuclear inelastic and screened coulombic scattering are all considered and programed. This software provides a function for calculating the statistical profile of energy deposition in sensitive volume of device. Using the spectrum of energy deposition for a specific device, the SEE rate is performed very well by defining the proper critical-deposited energy or critical charge.

The structure of multilayer stack in a hypothetical SRAM cell is shown in Fig. 1, which is composed of 5 μm silicon layer and 5 μm overlayers. A sensitive volume of 2 μm×2 μm×2.25 μm based on the Rectangular Parallelepiped model was centrally arranged the beneath of overlayers. For modeling the SEU occurrence induced by heavy-ion nuclear reactions, the interconnect layers of the device were simplified as 1.74 μm aluminum layer and 0.4 μm tungsten layer placed in the middle of SiO_2 layers.

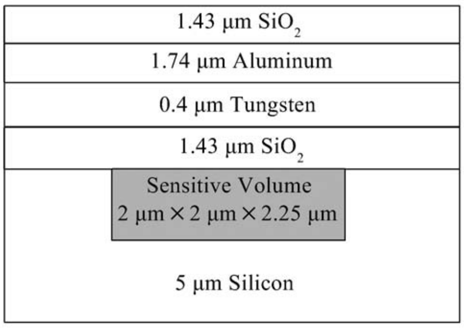

Fig. 1 The frame diagram of one SRAM cell architecture for simulation, with a surface area of 5 μm×5 μm (Not to scale).

In simulation, the sensitive volume was defined as the region in which the amount of energy deposited by incident ion is able to influence the performance of the device. For the calculation of SEU cross section, the critical charge (the minimum deposited charge in sensitive volume to induce a SEU occurrence) is given by[11,15]

$$Q_{\text{crit}}(\text{pC}) = 0.01035 \times LET_{\text{th}} \times d_{\text{SV}} \ , \tag{1}$$

where Q_{crit} is the critical charge, LET_{th} is the threshold LET, and d_{SV} is the depth of sensitive volume. If the deposited charge in sensitive volume is larger than Q_{crit}, then a SEU is considered as occurred. Therefore, the SEU cross section (σ) for a given Q_{crit} is calculated using the following equation,

$$\sigma(Q_{\text{crit}}) = \frac{\text{Events}}{\text{Fluence/cm}^2} = \frac{S}{N} \sum_{i=i(Q_{\text{crit}})}^{\infty} n_i \ , \tag{2}$$

where S is the surface area of the SRAM cell in Fig. 1, N is the total number of incident ions on the SRAM cell. In addition, the i^{th} ion is assumed to penetrate into the SRAM cell and create the deposited charge Q_i. And then the number of events n_i can be obtained by

$$n_i = \begin{cases} 0 \ , & (Q_i < Q_{\text{crit}}) \ , \\ 1 \ , & (Q_i \geqslant Q_{\text{crit}}) \ . \end{cases} \tag{3}$$

Utilizing the above mentioned hypothetical SRAM cell and CRÈME-MC software package, the detailed mechanism of SEU occurrence induced by heavy-ion nuclear reactions was analyzed.

3 Results and discussion

To investigate the impact of heavy-ion nuclear reactions on SEU, the SEU cross sections were calculated by two modes of simulation: (1) only direct ionization included; (2) direct ionization combining with nuclear reaction included. In simulation, the surface of the device depicted in Fig. 1 was set perpendicular to the direction of ion's penetration. Table 1 shows the main parameters of ion species, energy, LET, and range in silicon, which were input into CRÈME-MC program to model the upset process. For a given critical charge of 0.89 pC (equivalent to the threshold LET of 38.21 MeV·cm^2·mg^{-1}), the typical curves of SEU cross section as a function of LET were obtained, as shown in Fig. 2. It is clear that, in the saturated area of SEU cross section, the data simulated by the first mode has a good consistency with that by the second mode. Therefore, it is inferred that the secondary ions from heavy-ion interaction with device materials have a less impact on the saturated area of SEU cross section.

Table 1 Heavy-ion parameters in silicon used in Monte Carlo simulation for the prediction of SEU cross section

Ion	Energy/MeV	LET /(MeV·cm^2·mg^{-1})	Range (in silicon)/μm
^{197}Au	2 000	85.37	108.07
^{195}Pt	4 500	67.70	251.89
^{132}Xe	2 600 ~ 5 800	54.86 ~ 27.90	117.60 ~ 609.63
^{84}Kr	1 300 ~ 5 500	25.19 ~ 9.90	174.75 ~ 1 480
^{63}Cu	2 000 ~ 5 000	10.07 ~ 5.65	518.63 ~ 2 280
^{40}Ar	1 500 ~ 3 600	4.06 ~ 2.12	970.73 ~ 4 260

Nevertheless, below the saturated area of SEU cross section, the curve simulated by the second mode with a long tail exhibits a shift to the left of horizontal coordinate. In contrary, the simulated curve of the first mode has a sharp decline without dragging a long tail, and no SEU occurrence was observed below the LET of 34.03 MeV·cm^2·mg^{-1}. It means that the threshold

LET of SEU occurrence has a big extension to the origin of coordinate when direct ionization and nuclear reaction are taken into account together in simulation. According to Refs. [8,11,14], the extension of threshold LET is attributed to the nuclear reactions between heavy ions and device materials. In fact, the secondary ions produced by nuclear interactions are able to trigger the SEU occurrence, which is also proved by our simulation result. Additionally, the SEU cross section induced by secondary ions is generally less several orders of magnitude than the counterpart by direct ionization due to the extremely low probability of nuclear reactions (see in Fig. 2).

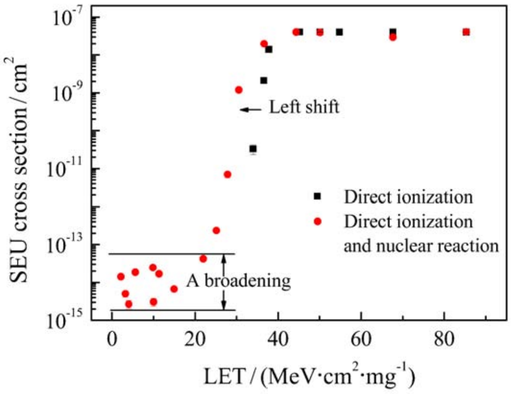

Fig. 2 (color online) The typical curves of SEU cross section versus LET were obtained by two different configurations of simulation.

Furthermore, it is noted that the SEU cross sections at relative low LET (approximately less than 20 MeV·cm^2·mg^{-1}) do not display a regular change with LET but a broadening along to the vertical coordinate. In order to better understand this broadening of SEU cross section and then accurately describe the SEU data, ^{40}Ar, ^{63}Cu and ^{84}Kr ions were employed to model the contribution of nuclear reactions to SEU cross section. The simulations were completed by the second mode with the ion energy from 1 000 to 10 000 MeV.

As shown in Fig. 3, the SEU cross section is plotted as a function of ion LET and energy, respectively. It is revealed that the SEU cross sections for ^{40}Ar and ^{63}Cu ions all display a parabolic relationship at two kinds of coordinate systems. But for ^{84}Kr ions, exception of a parabolic shape observed in Fig. 3(a), the SEU cross section also exhibits a rising trend as the LET is larger than about 20 MeV·cm^2·mg^{-1}. Similarly, such a variation trend for ^{84}Kr ions is also observed in Fig. 3(b). From 2 000 to 10 000 MeV, the LET of ^{84}Kr ions decreases slowly with ion energy and the maximum LET is about 19.32 MeV·cm^2·mg^{-1} at 2 000 MeV, which is far smaller than the threshold LET of SEU. In this case, the SEU occurrence is mainly induced by the secondary ions from nuclear reaction. But from 1 000 to 2 000 MeV, the LET of ^{84}Kr ions decreases rapidly from 28.89 to 19.32 MeV·cm^2·mg^{-1}, which is close to the threshold LET of SEU. As a result, the direct ionization may gradually dominate the SEU occurrence. Thus, the SEU cross section induced by ^{84}Kr ions shows an increasing trend when the LET is larger than about 20 MeV·cm^2·mg^{-1}. According to the description above, it is concluded that, even for the same ion species, the SEU cross section dose not vary monotonously with ion energy (or LET).

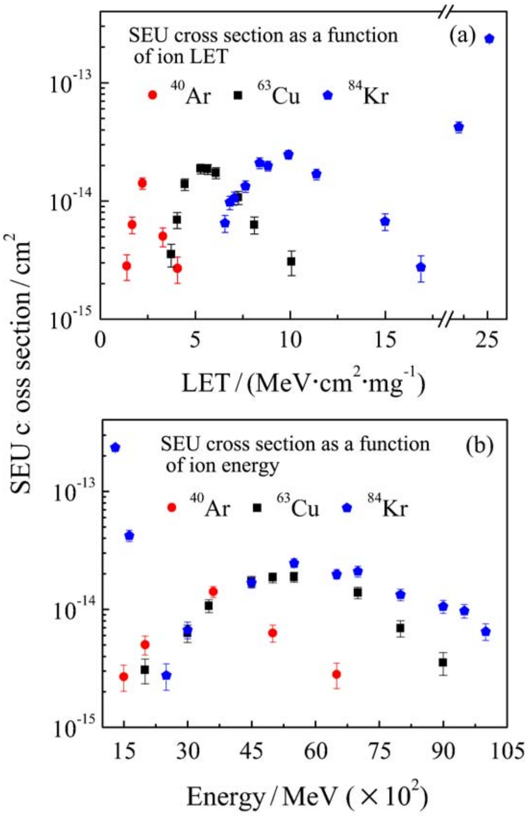

Fig. 3 (color online) Contribution of ^{63}Cu, ^{40}Ar and ^{84}Kr ions nuclear reactions to the SEU cross section.

Fig. 4 shows the curves of integral cross section versus deposited charge in sensitive volume for calculating the SEU cross sections induced by ^{84}Kr ions. In the light of the critical charge of a specific device, the corresponding SEU cross section can be derived from Fig. 4. For our simulated device, the critical charge has been set as 0.89 pC. Obviously, around the deposited charge of 0.89 pC, the variation trend of cross section with ion energy has a good agreement with the result in Fig. 3(b). However, at different range of deposited charge in Fig. 4, it is noted that the cross section has different variation relationships with ion energy. Thus, to some extent, the relationship between SEU cross section and ion energy also depends on what the critical charge is chosen.

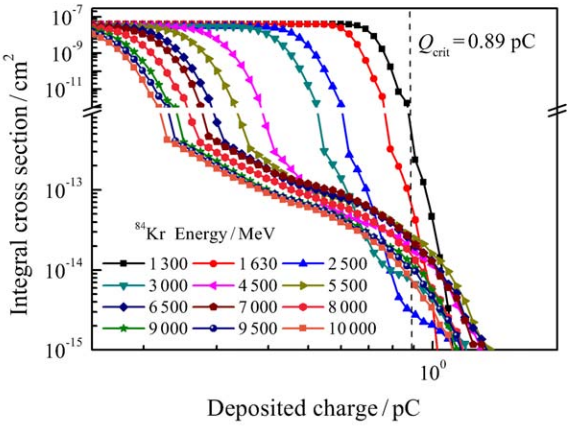

Fig. 4 (color online) The curves of integral cross section as a function of deposited charge in sensitive volume were plotted by considering direct ionization and nuclear reaction of ^{84}Kr ions.

For the same critical-charge, the SEU cross section induced by secondary ions may be related to the probability of nuclear reactions of the particular reaction channels. In the literature of Ref. [18], it is mentioned that only the LET of secondary ions larger than the threshold LET is able to induce the device error. For a specific secondary ions, the corresponding cross section of nuclear reaction is generally as a function of ion energy (be known as Excitation Function)[19−20]. In essence, the rate of SEU occurrence induced by heavy-ion nuclear reaction should depend on ion energy and species rather than ion LET, which may dominate the broadening of SEU cross section in Fig. 2.

As mentioned above, the SEU cross section induced by secondary ions does not have a gradient relationship with LET, for the same LET value but different heavy ions, the value of SEU cross section will be scattered to same extent, as shown in Fig. 2 and Fig. 3(a). On the other hand, even we take the SEU cross section as a function of ion energy in Fig. 3(b), the SEU data measured using different ions is still not described by ion energy due to the SEU cross section also depending on ion species.

In addition, ion energies and species provided by ground facilities are very limited, and it's not possible for us to measure the SEU cross section induced by nuclear reactions using all kinds of heavy ions with a large energy range. Therefore, there may not be an effective method to accurately characterize the SEU data induced by heavy-ion nuclear reactions.

However, based on the limited experimental data, as well as the computational simulation, it is still possible to give an approximate estimation for the SEU rate prediction. It is recommended that, researchers had better take the worst case to predict the on-orbit SEU rate. For instance, the peak value of each parabolic curve in Fig. 3(a) is considered as the worst case to calculate the SEU rate in space, which method will at least greatly ensure the reliability of prediction. Thus, the more ion species and the wider range of ion energy used in ground test, the prediction of the rate of SEU occurrence induced by heavy-ion nuclear reactions will be more accurate.

4 Conclusion

The SEU occurrence induced by heavy-ion direct ionization and indirect ionization were systematically studied by Monte Carlo simulation in a hypothetic SRAM cell. The simulation was carried out under the mode of only considering direct ionization and the mode of considering both direct ionization and nuclear reaction, respectively. The results show that, the typical curve of SEU cross section versus LET simulated by the second mode displays a shift to the left of horizontal coordinate with a long tail. Meanwhile, it is found that the SEU cross section simulated at the LET value less than about 20 MeV$\cdot$cm$^2\cdot$mg^{-1} has a broadening along to the vertical coordinate. The further analysis indicates that, the non-monotonic relationship between the heavy-ion nuclear reactions induced SEU cross section and ion energy is responsible for this broadening. According to the results above, it is suggested that the worst case of SEU occurrence induced by heavy-ion nuclear reactions should be considered to predict the on-orbit SEU rate.

Acknowledgement The simulated portion in this work was performed using the CRÈME-MC program developed by Vanderbilt University. The authors would like to thank Robert A. Weller and other researchers for updating and perfecting the CRÈME-MC tool.

References:

[1] LIU J, DUAN J L, HOU M D, *et al.* Nucl Instr And Meth B, 2006, **245**: 342.

[2] YANG S Y, CAO Z, DA D A, *et al.* Chin Phys B, 2009, **33**(5): 369.

[3] REED R A, KINNISON J, PICKEL J C, *et al.* IEEE Trans Nucl Sci, 2003, **50**(3): 622.

[4] LI Y H, HE C H, ZHAO F Z, *et al.* Nucl Instr And Meth B, 2009, **267**: 83.

[5] ZHANG Q X, HOU M D, LIU J, *et al.* Nucl Instr And Meth B, 2003, **209**: 367.

[6] GUO Hongxia, LUO Yinhong, YAO Zhibin, *et al.* Atomic Energy Science and Technology, 2010, **44**(12): 1498. (in Chinese)
(郭红霞, 罗尹虹, 姚志斌, 等. 原子能科学与技术, 2010, **44**(12): 1498.)

[7] HEIDEL D F, MARSHALL P W, PELLISH J A, *et al.* IEEE Trans Nucl Sci, 2009, **56**(6): 3499.

[8] REED R A, WELLER R A, MENDENHALL M H, *et al.* IEEE Trans Nucl Sci, 2007, **54**(6): 2312.

[9] KOGA R, CRAIN S H, CRAWFORD W R, *et al.* IEEE Trans Nucl Sci, 1998, **45**(6): 2475.

[10] DODD P E, MUSSEAU O, SHANEYFELT M R, *et al.* IEEE Trans Nucl Sci, 1998, **45**(6): 2483.

[11] WARREN K M, WELLER R A, MENDENHALL M H, *et al.* IEEE Trans Nucl Sci, 2005, **52**(6): 2125.

[12] REED R A, WELLER R A, SCHRIMPF R D, *et al.* IEEE Trans Nucl Sci, 2006, **53**(6): 3356.

[13] XAPSOS M. IEEE Trans Nucl Sci, 1992, **39**(6): 1613.

[14] DODD P E, SCHWANK J R, SHANEYFELT M R, *et al.* IEEE Trans Nucl Sci, 2007, **54**(6): 2303.

[15] WELLER R A, MENDENHALL M H, REED R A, *et al.* IEEE Trans Nucl Sci, 2010, **57**(4): 1726.

[16] MENDENHALL M H, WELLER R A. Nucl Instr And Meth A, 2012, **667**: 38.

[17] ADAMS J H, JR, BARGHOUTY A F, *et al.* IEEE Trans Nucl Sci, 2012, **59**(6): 3141.

[18] CAVROIS V F, SCHWANK J R, LIU S, *et al.* IEEE Trans Nucl Sci, 2012, **59**(4): 1149.

[19] HESS E, TAKACS S, SCHOLTEN B, *et al.* Radiochim Acta, 2001, **89**: 357.

[20] LU Xi Ting. Nuclear Physics[M]. Beijing, Atomic Energy Press, 2000: 238. (in Chinese)
(卢希庭. 原子核物理[M]. 北京: 原子能出版社, 2000: 238.)

重离子核反应对单粒子翻转的影响

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摘要： LET作为一个传统的工程参量，并不能完全满足单粒子翻转数据表征的需要，而且也不能直接地反映核反应的一些特性(包括核反应概率与次级粒子)，因此研究了重离子与器件作用过程中核反应对单粒子翻转的影响。基于蒙特卡罗模拟与深入的分析，本研究对比了在直接电离与考虑核反应两种模式下的模拟结果。在模拟中，利用不同的重离子表征了核反应在单粒子翻转发生中所起的作用。结果显示，核反应对单粒子翻转截面的贡献依赖于离子的能量，并呈现非单调的变化关系。基于模拟的结果，建议用重离子核反应引起单粒子翻转的最恶劣情况来预估空间单粒子翻转率。

关键词： 单粒子翻转；线性能量转移；核反应；重离子

收稿日期： 2014-03-05； **修改日期：** 2014-04-18

基金项目： 国家自然科学基金资助项目(11179003, 10975164, 10805062, 11005134)

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