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Reliability Assessment of Nanoscale System on Chip Depending on Neturon Irradiation / Yang, Weitao; Li, Yang; Hu, Zhiliang; He, Chaohui; Cai, Jiale; Wu, Longsheng. - In: ELECTRONICS. - ISSN 2079-9292. - (2023).

Availability: This version is available at: 11583/2978090 since: 2023-04-21T07:04:08Z

Publisher: MDPI

Published DOI:

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Reliability Assessment of Nanoscale System on Chip Depending on Neturon Irradiation

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The atmospheric neutron poses a serious hazard to nanoscale electronics reliability. Spallation neutron irradiations on a nanoscale system on chip (SoC) were conducted applying the China Spallation Neutron Source (CSNS), and the results were compared and analyzed using Monte Carlo simulation. The contribution from thermal neutron on the SoC single event effect (SEE) was analyzed. Analysis indicated the SoC atmospheric neutron SEE vulnerability can be reduced by 44.4% if the thermal neutron was absorbed. The influences of the B and Hf elements on the SEEs were evaluated, too. It can be concluded that ¹⁰B interacting with thermal neutron is the reason for thermal neutron inducing SEE in the SoC. Although the Hf element has no contribution to the 28 nm SoC atmospheric neutron SEE cross section, it increases the total dose risk 5 times during atmospheric neutron irradiation.

Keywords: Spallation Neutron; Monte Carlo; System on Chip; Thermal Neutron; Single Event Effect

1 2 **1. Introduction**

In 2001, Robert C. Baumann first reported ¹⁰B interacting with thermal neutron is a dominant 3 factor in soft errors for deep-submicron static random access memory with boro-phospho-4 silicate glass (BPSG) packages.^[1] Since then, advanced integrated circuit development makes 5 the chip packages get rid of the BPSG package.^[2-3] The nanoscale electronics, however, even 6 though the BPSG package is not available anymore, they have to face the risk from ¹⁰B 7 interacting with thermal neutron once again.^[4-7] The reason is ¹⁰B still existing in the 8 9 semiconductor contact and doping processes, and the rapidly developed semiconductor manufacturing technology pushes their supply voltages and single event effect (SEE) critical 10 charges lower and lower. 11

In [6], C. Weulersse examined a variety of memories taking advantage of multi neutron 12 sources and pointed out the related reliability problem. SEE, induced by ¹⁰B in nanoscale 13 14 memories via interacting with thermal neutron, is even close to that caused by high energy neutrons. In [8], the 65 nm microcontroller unit (MCU) without BPSG was irradiated with 15 thermal and high energy neutrons, and the influence of ¹⁰B on SEE was investigated. The 16 results demonstrated that the contribution of ¹⁰B interacting with thermal neutron even 17 dominated the atmospheric neutron SEE in the device. Specifically, the SEE ratio induced by 18 thermal and higher energy neutrons on the 65 nm MCU reached 1.89:1.^[8] 19

The 65 nm MCU test results signify that the interaction of ¹⁰B with thermal neutron is still serious to advanced integrated chips. For the 28 nm SoC, besides the boron contamination, another is also introduced: the hafnium (Hf) element. Compared with boron (B), the neutron cross section with Hf is higher at several eV intervals. Fig.1 displays the neutron cross section spectrums of ¹⁰B, ¹⁷⁸Hf, and ²⁸Si.^[9] It can be viewed the peak cross section of ¹⁷⁸Hf even achieves 10⁵ barns. The cross sections of ¹⁷⁸Hf with thermal neutron are also higher than that of ²⁸Si by two orders of magnitudes. Another significant fact is that the B element exists in the 28 nm SoC as the contamination from manufacturing processes, while the Hf element is a
 component of the metal gate in the 28 nm SoC. This process makes the 28 nm SoC atmospheric
 neutron SEE evaluation become more complicated.

For the 28 nm SoC atmospheric neutron SEE, the first irradiation test has been conducted at 30 the China Spallation Neutron Source (CSNS)-BL09.^[10] In the irradiation, the neutron beam 31 hited the chip directly without any shield, and the neutron spectrum covered the thermal and 32 33 high energy neutrons. To explore the atmospheric neutron SEE on the 28 nm SoC further, the second irradiation on the SoC was performed once more. But a 2 mm cadmium (Cd) slat was 34 used to absorb the thermal neutron before the irradiated chip compared with the previous. By 35 36 comparing the two irradiation results, thermal neutron's contribution to the 28 nm SoC can be investigated. Meanwhile, the B and Hf elements' influence can be analyzed from the irradiation 37 and the Monte Carlo simulations. 38

39 2. Irradiation Tests

The actual atmospheric neutron SEE test is time-consuming, and the spectrum of the spallation neutron source is the closest to the real one. Thus, it is considered the ideal atmospheric neutron source.^[11] Scale-down manufacturing technology makes it urgent to undertake more available atmospheric neutron SEE irradiation studies. The China spallation neutron source was implemented in 2018 and made it come true to launch atmospheric neutron SEE tests using a spallation neutron source in China.^[12] Fig.2 shows the calculated differential flux of the neutron beam of CSNS (10⁹ of Peking ground).

Based on the CSNS-BL09, two SEE irradiation tests were conducted on the 28 nm SoC. In [10], the first irradiation test was performed, and the SoC was irradiated by the neutron beam directly without any shield. In the second irradiation test, that is the current work, a 2 mm Cd slat was placed between the beam ejection stop and the tested chip to absorb thermal neutrons. Fig.3 displays the neutron spectrum at the terminal with and without the 2 mm Cd slat [^{8]}. It can be seen that the 2 mm Cd slat absorbs the neutrons effectively whose energies are below 0.5 eV.

The on-chip memory (OCM) block of the Xilinx Zynq-7000 SoC was tested in two irradiations. The 64 kB data in the OCM were tested dynamically. The check pattern data, 0xA5A5A5A5, were written into the OCM addresses and read back by the SoC, and the SoC compared the readback one with the check pattern data to determine whether a SEE took place. The comparison results was moved to PC and refreshed in a termial. It requires to compare results with the first irradiation, where the normal condition is examined without any mintigation techniques. Hence, the same condition is available in this effort.

In both irradiations, the test establishments are the same except the 2 mm Cd slat. A 2260B programming DC power supplied the test board. The real-time current was monitored and recorded by the remote host computer, and the possible single event latch-up was also investigated. The host computer and the test board communicated through a universal serial bus cable, and the running messages were recorded in real-time.

66 3. Results and Discussions

Four kinds of soft errors were detected in both irradiations, including the single bit upset (SBU), dual cell upset (DCU), multi-cell upset (MCU), and single event functional interruption (SEFI). No abnormal current was detected, which means no latch-up event emerged in the 28 nm SoC atmospheric neutron SEE irradiation tests. However, there are some differences between the two irradiations in terms of SEE cross section. This discrepancy signifies thermal neutron impacts the 28 nm SoC atmospheric neutron SEE.

73 **3.1. The Detected Events**

In the second irradiation, 19 events were detected. Table I lists the number of each type of error. The number of SBU events is more than others. It is similar to that in the first irradiation. During the second irradiation, the neutron flux above 1 MeV was about $6.85 \times 10^5 \,\text{n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ and the corresponding fluence was $2.47 \times 10^{10} \,\text{n} \cdot \text{cm}^{-2}$. Hence, the SBU cross section is $(5.26 \pm 0.26) \times 10^{-10} \,\text{cm}^2$ and $(1.00 \pm 0.05) \times 10^{-15} \,\text{cm}^2 \cdot \text{bit}^{-1}$ for the irradiation with few thermal neutrons.

80

Table I. The detected SEE in irradiation with few thermal neutrons

	SBU	DCU	MCU	SEFI		
_	13	2	2	2		
81	Table II. The detected SEE in irradiation with thermal and high energy neutrons. ^[10]					
	SBU	DCU	MCU	SEFI		
_	21	4	2	5		

82

Table II presents the detected SEE in the first irradiation. It can be seen the number of SBU events is 21 in the irradiation, which is also more than others. In Table I and II, it is evident that SBU events dominate the detected soft errors in both irradiations.

Table III presents the SBU cross sections in two irradiations. The neutron fluence of the 86 second irradiation is 2.47×10^{10} n·cm⁻², higher than that of the first irradiation by 11.26%, 87 however, the number of SBU event in the second irradiation is 13 instead of more than 21. This 88 89 phenomenon implies thermal neutron has a contribution to the 28 nm SoC atmospheric neutron SEE. The discrepancy between the bit cross sections is 0.8×10^{-15} cm²·bit⁻¹. Since the critical 90 difference between two irradiations is containing thermal neutron or not, it can be speculated 91 thermal neutron causes the discrepancy. It attests the SEE sensitivity of the 28 nm SoC can be 92 93 reduced by about 44.4% by shielding thermal neutron with a 2 mm Cd slat. All these 94 demonstrate that risks from thermal neutron cannot be neglected, even though the nanoscale 95 chips get rid of BPSG in packages.

Neutron Beam	Fluence $10^{10} \mathrm{cm}^{-2}$	SBU	Cross section $10^{-10} \mathrm{cm}^2$	Bit cross section 10 ⁻¹⁵ cm ² ·bit ⁻¹
CSNS-BL09 ^[10]	2.22	21	9.46±0.47	$1.80{\pm}0.09$
CSNS-BL09+2mm Cd	2.47	13	5.26±0.26	$1.00{\pm}0.05$

Table III. The SBU cross sections in two irradiations.

97

96

98 **3.2. B Influence**

The 65 nm MCU atmospheric neutron irradiation results indicated that the secondary particles from thermal neutrons interacting with ¹⁰B could result in SEU on advanced electronic systems. Compared with the 65 nm memory cell, the SEU critical charge of the 28 nm memory cells is lower, and thermal neutron is easier to induce soft errors in the 28 nm process cells.

103
$${}^{10}\text{B}+n_{\text{th}} \rightarrow {}^{7}\text{Li}(1.01 \text{ MeV})+\alpha(1.78 \text{ MeV})$$
 (3-1)

104
$${}^{10}\text{B}+n_{\text{th}} \rightarrow {}^{7}\text{Li}(0.84 \text{ MeV})+\alpha(1.47 \text{ MeV})+\gamma(0.48 \text{ MeV})$$
 (3-2)

Formulas (3-1) and (3-2) describe the mechanisms of thermal neutron (n_{th}) reacting with ¹⁰B. The probability of (3-1) is 6.3%, and that of (3-2) is 93.7%.^[13] It means the key of thermal neutron inducing SEE in the 28 nm SoC is ⁷Li(0.84 MeV) and α (1.47 MeV) particles. They deposit energy in the sensitive volumes. Table IV shows the ranges in silicon and the linear energy transfers (LETs) of the two secondary particles.^[14] The ranges in silicon of α (1.47 MeV) and ⁷Li(0.84 MeV) are just 5 µm and 2.5 µm, which are much less than the thickness of the 28 nm SoC from top passive layers to substrate's surface.^[15] This phenomenon preliminarily

reveals that the B contamination exists inner the chip and approaches sensitive volumes of the

- 113 SoC. The SEE LET threshold of the 28 nm cell is approximately 0.50 MeV·cm²·mg⁻¹.^[16] For
- 114 ⁷Li(0.84 MeV) and α (1.47 MeV), the LETs are 2.10 MeV·cm²·mg⁻¹ and 1.15 MeV·cm²·mg⁻¹,
- respectively. They are higher than the threshold, which means both secondary particles can
- 116 induce SEE in 28nm SoC.
- 117

Table IV. The ranges and LETs of secondary particles of ¹⁰B with the thermal neutron.

Rang in sili	con/µm	LET/MeV·cm ² ·mg ⁻¹		
⁷ Li(0.84 MeV)	α(1.47 MeV)	⁷ Li(0.84 MeV)	α(1.47 MeV)	
2.5	5	2.10	1.15	

118 It is different from the 65 nm MCU, the Hf element also exists inner the 28 nm SoC, and the 119 cross section of Hf with thermal neutron is even higher than that of silicon. Thus, it cannot 120 conclude the difference is induced by 10 B directly.

121 **3.3. Hf Influence**

¹⁰B, in the 28 nm SoC, interacts with thermal neutron inducing SEE, that mainly comes from the high probability of nuclear reaction. However, as Fig.4 displays, the primary interaction of thermal neutron and the Hf element is the (n, γ) reaction,^[9] and the γ rays usually results in total ionization dose rather than SEE in the device.^[17] Because the generated γ rays cannot cause SEE directly and have to interact with other atoms to produce secondary heavy ionization particles, this possibility is relatively low.

128 Compared with high energy neutrons, cross sections of 178 Hf interacting with the eV level 129 neutrons even achieve 10^5 barns. In this case, whether the hafnium element contributes to 28 130 nm SoC atmospheric neutron SEE, required to be comprehensively assessed.

In Fig.4, the peak's reaction of ¹⁷⁸Hf with several eV neutrons is elastic or (n, γ) . As mentioned above, the contribution from (n, γ) reaction to induce SEE in 28nm SoC is rather low. Neutron in elastic interaction can transfer energy to hafnium atoms, it might increase the probability of causing SEE. The maximum transfer energy to the Hf atom from neutron can be calculated with the formula (3-3). ^[18]

136
$$Et = \frac{4MnMt}{(Mn+Mt)^2}En (3-3)$$

Et is the max energy transfer to Hf atom with keV, Mn is the mass of the neutron, which is 138 1.67×10^{-27} kg, Mt is the Mass of Hf and it is 2.96×10^{-25} kg, and En is the energy of neutron 139 with keV.

The current work mainly discusses soft error in the 28 nm SoC induced by thermal neutron 140 reacting with the boron and hafnium elements. As stated in Section 2, the neutron with energy 141 142 less than 0.5 eV are obsorbed by a 2 mm Cd slat. For the 0.5 eV neutron, the maximum transferred energy to Hf atom is about 0.01 eV. Meanwhile, considering the peak elastic cross 143 144 section in Fig. 4, even though it extends the neurton energy to the rightmost peak, the corresponding max transferred energies are lower than 0.03 keV. Considering their LETs (the 145 corresponding LETs are less than 0.50 MeV·cm²·mg⁻¹), these are all impossible to lead to SEE 146 147 on the SoC. It testifies the high cross section elastic interaction from Hf with thermal and eV 148 neutrons does not affect 28nm SoC atmospheric neutron SEE.

149 Hence, it can be concluded the soft error difference between the two irradiations is mainly 150 caused by ${}^{10}B$.

151 **3.4. Monte Carlo Simulation**

The cut cross section of the chip is investigated and captured, as shown in Fig. 5, the thickness and materials of the passive layers were obtained.^[10, 15] Meanwhile, the 28 nm Highk metal gate (HKMG) technology gate contains TiN(8 nm), HfO₂(10 nm), and SiON(1.2 nm),^[19] and the ultra-thin SiON layer can also be an ultra-thin SiO₂ layer in the HKMG technology.^[20] Relying on these effort and information, two Geant4 Monte Carlo simulation models were constructed to examine the Hf element's influence.^[21, 22] In Fig.6, the TiN and ultra-thin SiO₂ layers are considered only in the first model, while the TiN, HfO₂, and ultrathin SiO₂ layers are considered simultaneously in the second model in Fig.7. Others are the same for the two simulation models.

161 The spectrum of neutron sources in the simulation is the same as in the first irradiation test, 162 which includes thermal and high energy neutrons. The number of neutrons is 10^7 , and the 163 surface area of the model is $10 \ \mu m \times 10 \ \mu m$. 32×32 sensitive volumes (SVs) are placed, the size 164 of the volume is $130 \ nm \times 130 \ nm$, and the critical charge is 0.18 fC. During the 165 simulation, if the deposited energy in an SV overs the critical charge in an EventAction, which 166 means an SEU emerged.

The number of the upset event in the cells and deposited doses in the ultra-thin SiO₂ layer 167 168 were recorded in both simulations and shown in Table V. It can be seen the number of the upset event and the cross section are the same in both simulations. Still, the deposited dose in the 169 ultra-thin SiO₂ layers differs by almost 5 times. The simulation results verify that the Hf 170 element does not influence 28 nm SoC atmospheric neutron SEE. However, the existence of 171 172 hafnium may increase the total dose risk during atmospheric neutron SEE irradiation. In Fig.4, the high (n, γ) cross section also underlines this possible outcomes, because more γ rays means 173 more possible total ionization dose risk. And the simulation results is consistent with that. It 174 175 suggests total dose risk monitoring is necessary in much more fluence atmospheric neutron

176 SEE irradiation tests for the SoC.

177

Table V. The upset number and deposited doses in two simulations.

Upset number		Bit cross se	ction/cm ² ·bit ⁻¹	Deposited Dose/rad	
First Model	Second Model	First Model	Second Model	First Model	Second Model
5	5	5×10 ⁻¹⁶	5×10 ⁻¹⁶	12.6	63.3

Up to now, we evaluated the 65 nm MCU and 28 nm SoC atmospheric neutron SEE
depending on CSNS. In the future, more SEE irradiations and assessments will be explored
further.

181 4. Conclusion

The 28 nm SoC was irradiated twice at CSNS-BL09. In the first irradiation, the specture covered the thermal and high energy neutron, while thermal neutrons were shielded in the second. The differences in the results were analyzed. The discrepancy between the two irradiation tests is caused by ¹⁰B interacting with thermal neutron. If thermal neutron in the atmospheric environment is shielded by a 2 mm Cd slat, the 28 nm SoC SEE sensitivity can be decreased by 44.4%. The hafnium element does not influence the 28 nm SoC atmospheric neutron SEE, although it also has a high interaction cross section with thermal neutron. The evaluation illustrated attention should be paid to total dose hazard during the 28 nm SoC atmospheric neutron SEE irradiation, since the hafnium element increases the total dose risk.

182

183 Acknowledgment

184 Authors thank the engineers of CSNS-BL09.

185 Project supported by National Natural Science Foundation of China (Grant Nos. 11575138,

- 186 11835006, 11690040, and 11690043)
- 187

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