Cosmic Ray Background Effects on the Neutron Intercepting Silicon Chip (NISC)

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Introduction

Cosmic rays primarily consist of galactic and solar particles, and continuously penetrate the earth's atmosphere. Solar particles originate from the sun with energies of up to 1 GeV, with particle fluxes dependant on the 11-year period solar cycle. However, due to interactions with the atmosphere, almost all of the solar particles are absorbed atmospherically, creating no particles at sea level. On the other hand, galactic particles, mainly protons, have enormous energies (up to 10^8 GeV) and create cascades of particles that can also generate secondary cascades of particles [1, 2]. Even if 1 % of the incident galactic particles have enough energy to cause cosmic rays at sea level, produced cosmic rays, almost 97 % of them are thermal neutrons at sea level that can induce soft errors in electronics. Furthermore, the cosmic ray flux changes exponentially by the altitude in the atmosphere.

The Neuron Intercepting Silicon Chip (NISC), a new unconventional neutron sensor/detector system which is being developed at The Pennsylvania State University, is designed to enhance soft errors in semiconductor memories by introducing ^{10}B-enriched Borophosphosilicate glass (BPSG) insulation layers in the semiconductor memory. Major soft error enhancement comes from the ^{10}B (n, α[1.47 MeV]) ^{7}Li [0.84 MeV] reaction in the BPSG layers and both reaction products can induce soft errors or single event upsets in the memory. The NISC is sensitive to thermal neutron measurements since the reaction cross sections depend on incoming neutron energy and due to its high value in thermal energies (3837 barns at 0.0253 eV). Since the NISC is mainly sensitive to the thermal neutrons, only the contribution of cosmic ray-induced soft errors in the NISC will be presented in this paper. Nuclear simulations with basic silicon-based semiconductor memory device node models for different altitudes in the atmosphere and ^{10}B content in the BPSG layers will be presented in order to investigate the soft error rate (SER) in the NISC. Supplying only the required critical charge of the device in nuclear simulations will represent the coupling of nuclear simulations with solid-state device simulations.

An analysis tool, the NISC Soft Error Analysis Tool (NISCSAT), was developed for the simulation of the charged particle interactions in the semiconductor memory model. NISCSAT performs the particle transport and tracking via Geant4 [3]. The authors also published experimental results for soft error rate dependency on the neutron flux and the operating voltage of the memory and soft error modelling of the NISC with thermal neutrons [4, 5].

Cosmic Ray and NISC Simulation Model

The semiconductor device node represents the basic data storage unit in a semiconductor memory, and the NISC was designed to be as simple as possible in order to focus on the ^{10}B(n,α)^{7}Li reaction, which is the main source of soft errors. Cosmic rays are modelled with the Cosmic Ray Shower Library (CRY) [6] from Lawrence Livermore National Laboratory. The CRY is based on pre-computed input tables derived from full MCNPX simulations of primary cosmic rays (1 GeV to 100 TeV primary particles) on a full atmosphere model and enables a fast simulation of the cosmic rays without any computational time requirement besides the SER simulation in the NISCSAT. The CRY is used by the NISCSAT at three different altitudes, sea level, 2100 m, and 11300 m, with coordinates set to New York City.

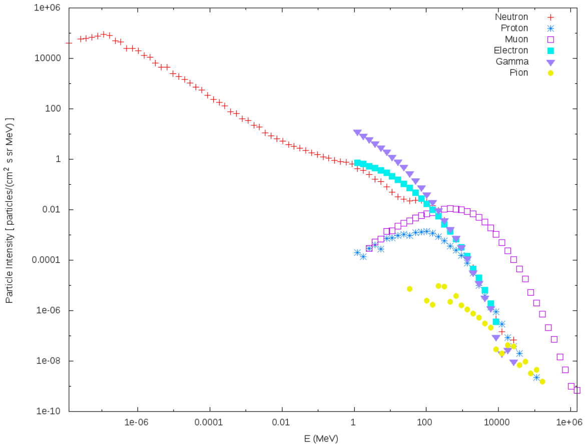

FIGURE 1: Cosmic rays at sea level.

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Calculated cosmic ray intensities at sea level are shown in Figure 1. CRY results are in good agreement with previously published cosmic ray flux values [7-14]. However, only downward cosmic particles are included in the CRY and cosmic thermal neutron energy spectrum differs from the measured data due to neutron scattering and moderation at sea level.

Since the NISC is sensitive to the thermal neutrons, a modified cosmic thermal neutron energy spectrum, taken from the JEDEC [15] standard, is also used for a more realistic sea level neutron spectrum. Modification is only applied to the neutron spectrum during the source sampling and other particles' spectrums are not changed. Comparison of the CRY-generated neutron spectrum and JEDEC neutron spectrum at sea level is shown in the Figure 2. The shift in the neutron energy spectrum from fast to thermal energy regions caused by moderation and scattering from the earth surface is important for the NISC modelling and must be accounted for in the calculations.

The semiconductor device node, which can be considered as bit-cell or unit-cell, for the NISC design is as simple as possible in order to focus on the $^{10}B(n,\alpha)^{7}Li$ reaction. A cross-sectional view of the memory node model is illustrated in Figure 3. The BPSG layer is designed to produce energetic α and ^{7}Li particles, hence it acts as a source for producing soft errors. In semiconductor memory, depending on the architecture and vendors, there are different layers to produce depletion regions, gates, and isolation layers. The memory node represents the basic data storage unit in the semiconductor memory.

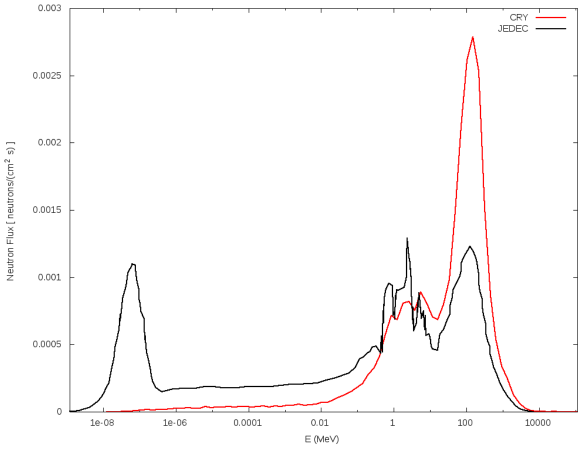

FIGURE 2: CRY and JEDEC cosmic thermal neutrons at sea level.

The BPSG materials are B^{ENR} (90 % ^{10}B) and BPSG (1 % ^{10}B) in order to better observe the efficiency of the NISC design. Node dimensions are chosen as 5 μm x ($t_B + t_S$) x 5 μm where t_B is the thickness of the BPSG and t_S is the silicon region thickness. BPSG thickness, t_B, is chosen as 2 μm in order to maximize the energy deposition of both reaction products since the range of the ^{7}Li [0.84 MeV] particle in boron is approximately 1.85 μm while the range of the α [1.47 MeV] particle is close to 3.5 μm. Critical charge for the node is assumed as 2.3 fC for all simulations. The entire silicon region is assumed to be a sensitive volume in which the induced excess charges will most likely cause soft errors. Cosmic rays are sampled as the source from the surface of the model.

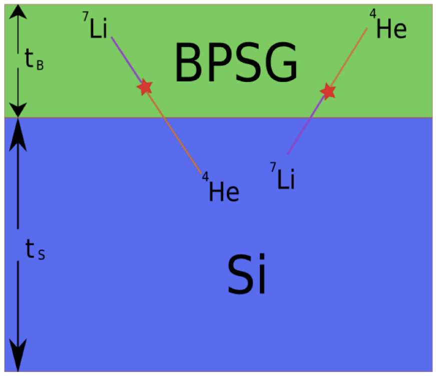

FIGURE 3: NISC node model.

Simulation Results

Soft error simulation results for the NISC node results at different altitudes are given in Table 1 and array results are given in Table 2. As altitude increases, soft error probability decreases since the energy spectrum of the neutrons shifts to the fast energy region. As expected, the modified neutron energy spectrum shows greater soft error probability compared to unmodified CRY results due to thermal neutrons. SER probability from the cosmic rays is negligible at sea level when compared to a mono-energetic thermal neutron source for the same NISC model, as published by the authors [4]. Cosmic ray-induced soft error probability is less than 2 % of the total soft errors for the thermal neutron sources. In addition, the calculated probabilities are normalized to cosmic ray flux; if the actual cosmic ray fluxes (approximately 0.01 n/cm^{2}s at sea level) were used, the soft error probability listed in Table 2 for cosmic rays would drop 100 times. Any thermal neutron source, located at such a distance that the neutron flux value is higher than 0.02 n/cm^{2}s, can be detected with negligible cosmic ray background. Even if the cosmic ray-induced SER results were disregarded, sea level cosmic thermal neutrons for the soft error calculations remain important since the scattered and slowed down neutron spectrum can have 10 times higher SER probability than only downward modeled cosmic thermal neutrons.

As published before [16, 17], the $^{10}B(n,\alpha)^{7}Li$ reaction is the major component of the soft error sources as shown in Tables 1 and 2. In addition to the cosmic thermal neutron-induced $^{10}B(n,\alpha)^{7}Li$ reactions, other cosmic particles, mainly muons, electrons, positrons, and protons also contribute to SER probability. These particles become more important as the feature size of

TABLE 1: NISC node simulation results with cosmic rays for 5x(2+1)x5 µm node, Q_{CRIT}= 2.3 fC (ENR: Enriched)

Altitude (km)	BPSG Material	Soft Errors		
		Mother Particle	Source Particles (%)	Probability (x10^{-9}) per flux (particles/cm^{2} s)
0	B^{ENR}	μ-	μ- (100)	0.003
	BPSG	μ-,μ+, e-	μ- (12), μ+ (63), e- (25)	0.028
0^{*a}	B^{ENR}	n,n, μ-,e-,e+	α (48),^{7}Li (24), μ- (14), e- (9),e+ (5)	0.074
	BPSG	n,μ-,μ+,e-	^{7}Li (20), μ- (20), μ+ (40), e- (20)	0.018
2100	B^{ENR}	n,n, μ-,e-,e+	α (42),^{7}Li (17), μ- (17), e- (8),e+ (16)	0.043
	BPSG	μ-	μ- (100)	0.003
11300	B^{ENR}	n,n, μ-,e-,e+	α (38),^{7}Li (13), μ- (12), e- (25),e+ (12)	0.029
	BPSG	e+	e+ (100)	0.003

a JEDEC neutron spectrum used with CRY

TABLE 2: NISC array simulation results with cosmic rays for B^{ENR}, 5x(2+1)x5 µm node, Q_{CRIT}= 2.3 fC

Altitude (km)	Array Config	Soft Errors			
		Mother Particles	Source Particles (%)	Probability (x10^{-9}) per flux (particle/cm^{2} s)	
				Total	Node
0^{a}	1000x1x1000	n,n, μ-, μ+,e-,e+,p	α (40),^{7}Li (30), μ- (7), μ+ (10),e- (6), e+(3), p(4)	2.38x10^{5}	0.238
	1000x2x1000	n,n, μ-, μ+,e-,e+	α (56),^{7}Li (28), μ- (9), μ+ (4),e- (2), e+(1)	5.26x10^{5}	0.263
	1000x5x1000	n,n, μ-, μ+,e-,e+,p	α (57),^{7}Li (21), μ- (6), μ+ (8),e- (3), e+(3),p(2)	1.26 x10^{6}	0.252
2.1	1000x1x1000	n,n, μ-, μ+,e-,e+	α (32),^{7}Li (25), μ- (11), μ+ (18),e- (7),e+ (7)	9.94 x10^{4}	0.099
	1000x2x1000	n,n,μ-, μ+,e-,e+,p	α (54),^{7}Li (23), μ- (6), μ+ (7),e- (3),e+ (3), p(4)	2.48 x10^{5}	0.124
	1000x5x1000	n,n,μ-,μ+,e-,e+,p	α (59),^{7}Li (20), μ-(3), μ+ (5), e- (5),e+ (2), p(6)	5.99 x10^{5}	0.120
11.3	1000x1x1000	n,n,e-,e+,p	α (54),^{7}Li (19), e- (8),e+ (8), p(11)	9.28 x10^{4}	0.093
	1000x2x1000	n,n,μ-,e-,e+,p	α (56),^{7}Li (20), μ- (2),e- (8),e+ (3), p(11)	2.18 x10^{5}	0.109
	1000x5x1000	n,n,μ-,μ+, e-,e+,p,n	α (55),^{7}Li (22), μ-(1),μ+ (2), e- (8),e+ (5), p(6), ^{10}B (1)	5.28 x10^{5}	0.106

a JEDEC neutron spectrum used with CRY

the memory decreases since the required charge will also decrease and soft errors will be triggered by particles that have lower linear energy transfer compared to alpha and lithium particles.

Summary

Cosmic ray modeling and cosmic particle-induced soft errors in the NISC are summarized in this paper. SER in the memory is analyzed by simulating the neutron interactions using Geant4-based SER simulation tool NISCSAT. NISCSAT was coupled with the CRY in order to simulate cosmic rays at different altitudes. Simulation results showed that the cosmic thermal neutron-induced SER is lower than 2 % in the NISC. Sensitivity analysis of the NISC with different neutron sources, environmental effects, and memory architectures are still in progress. NISCSAT will be integrated with the Soft Error Analysis Tool (SEAT) [18], which supports device level, circuit level, logic level, and architecture level soft error analysis.

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