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Multi-Poisson Process Analysis of Real-Time Soft-Error Rate Measurements in Bulk 65nm SRAMs

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Abstract

Altitude and underground real-time soft error rate (SER) measurements on SRAM circuits have been analyzed in terms of independent multi-Poisson processes describing the occurrence of single events as a function of bit flip multiplicity. Applied for both neutron-induced and alpha particle-induced SERs, this detailed analysis highlights the respective contributions of atmospheric radiation and alpha contamination to multiple cell upset mechanisms. It also offers a simple way to predict by simulation the radiation response of a given technology for any terrestrial position, as illustrated here for bulk 65nm SRAMs.

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Multi-Poisson Process Analysis of Real-Time Soft-Error Rate Measurements in Bulk 65nm SRAM

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1. Introduction

Real-time soft error rate (RTSER) technique is an experimental reliability method to determine the soft error sensitivity of a given component, circuit or system [1]. The methodology consists in a direct observation of a large number of devices working in parallel under standard operating conditions and exposed to ambient background radiation at ground level. From the detection and counting of single events upsets occurring during the experiment, one can estimate the soft error rate (SER) of the devices under test. In case of SRAM circuits, the result can be given in terms of "event" SER, "total bit flip" SER, "multiple cell upset" (MCU) SER, and can be numerically expressed in FIT/Mbit (one FIT equals one failure per 10^9 hours of operation) [2].

For modern CMOS circuits at terrestrial level, SER is the result of a weighting of two main components due to: i) the atmospheric particle flux and particularly the high-energy neutrons interacting with IC materials; ii) the traces of radioactive elements present in the circuit materials, mainly U or Th contaminations at sub-ppb concentrations. These two SER components are respectively labeled neutron-SER (n-SER) and alpha-SER (α-SER). Neutron-SER is proportional to the intensity of the high-energy neutron flux at test location whereas alpha-SER is fixed and linked to the concentrations of radioactive impurities. The measured SER at a given test location is generally expressed as [2,3]:

$$SER_{test\ location} = AF \times n\text{-}SER_{NYC} + \alpha\text{-}SER \qquad (1)$$

where AF is the so-called acceleration factor [3] which define the relative neutron flux at test location with respect to sea-level (reference New York City, NYC) and n-SER_{NYC} is the value of the neutron-SER normalized for NYC conditions. From Eq. (1), it is obvious that α-SER can be directly measured during an underground experiment (AF = 0) and that measurements at two different locations is sufficient for determining the two unknown quantities n-SER_{NYC} and α-SER.

In this study, altitude (on the ASTEP platform [2]) and underground (at LSM, Modane [4]) real-time soft error rate (SER) measurements on bulk 65nm SRAM circuits have been analyzed in terms of independent multi-Poisson processes describing the occurrence of single events as a function of bit flip multiplicity. This approach has been applied for estimating the event rates induced by atmospheric neutrons and alpha-particle emitters as a function of event multiplicity. We used these extracted results to predict by simulation the radiation response of the 65nm SRAMs for a third test location at sea-level (Marseille, France), illustrating the advantage of this method not only to evaluate the global SER value but also to accurately estimate the occurrence of MCU events as a function of their event multiplicity.

2. Theory

The occurrence of soft errors in electronics is a continuous time stochastic process. The principle of a RTSER experiment is to count the number of random events N(t) that have occurred up to some point t in time over a large population of circuits (the number of events is therefore small relative to the number of memory elements considered in the test). In such a real-time approach, soft errors are not permanent because they are eliminated when new data is written after detection: a RTSER test is thus equivalent to a life-test with replacement, i.e. in which a failing device is replaced with a new device immediately upon failure detection. Assuming that soft errors are also random in space (within the circuits), independent of each other and occur with a fixed event rate λ, the counting process $\{N(t),\ t \geq 0\}$ in a finite interval of time t consequently obeys the Poisson(λt) distribution [4]:

$$P(N(t)=n) = \frac{e^{-\lambda t}(\lambda t)^n}{n!},\ \text{n = 0, 1, 2} \qquad (2)$$

The maximum likelihood estimate for λ is simply the number of detected events N divided by the experiment duration T and eventually normalized with respect to the number of units on test. Expressing this later quantity in Mbit for a memory test and time in MBit×h, λ can be directly estimated from:

$$\lambda = N / \Sigma \tag{3}$$

where Σ is the number of MBit×h cumulated at time T given by:

$$\Sigma = \int_0^T MEM(t)\,dt \tag{4}$$

where MEM(t) represents the number of Mbit under test at time t. This quantity may be variable in case of device automatic disconnection by the system due to abnormal current consumption or other anomaly detected at device, daugthercard or mothercard levels.

The counting process, previously introduced, can be applied to "single events" (whatever the type of these events), or more specifically to single bit upsets (SBU) or to multiple cell upsets (MCU) defined by a given event multiplicity (noted MCU(q), q = 2, 3,.. corresponding to the number of bitcells simultaneously upset during a same particle interaction event). Let $N_1(t)$, $N_2(t)$,.... $N_i(t)$, ... $N_M(t)$ be M independent Poisson processes with event rates $\lambda_1, \lambda_2, \ldots, \lambda_i, \ldots \lambda_M$ respectively corresponding to the counting of SBU, MCU(2), ..., MCU(i),... MCU(M) events. The total event counting process $N(t) = \sum N_i(t)$ will be the merging of all these Poisson processes and will be also a Poisson process with rate $\lambda = \lambda_1 + \lambda_2 + \ldots + \lambda_i \ldots + \lambda_M$, as illustrated in Fig. 1.

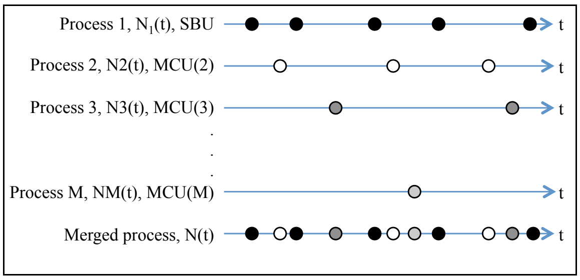

Figure 1. Merging M Poisson processes corresponding to the occurrence of single events of different cell upset multiplicities.

Performing such a multi-Poisson process decomposition of the global "single event" process occurring during a RTSER experiment will allow us to reveal the respective contributions of atmospheric neutrons and alpha-particle emitters in the MCU SER response of the technology under test, as illustrated in the following.

3. Real-time experiments

For the purpose of this study, we considered raw data of three RTSER experiments performed on 3,226 Mbit of bulk 65nm Single-Port SRAMS (using two identical test setups) between 2008 and 2017. Details about these experiments can be found in Refs. [2, 5-7]. Table I summarizes these experiments conducted on the ASTEP platform (2,255 m of altitude) in 2008-09, at the underground laboratory of Modane (LSM) between 2008 and 2015 and at sea-level in Marseille (IM2NP laboratory) since 2014. This last experiment is always running in 2017.

Table 1. Summary of the 65nm SRAM RTSER experiments.

Location	Acceler. factor AF	Start date Stop date	Effective cumulated hours of tests
ASTEP	6.5	01/21/2008 05/07/2009	11,278
LSM	0	04/11/2008 01/25/2015	57,058
Marseille	0.9	10/16/2014 Ongoing*	17,233

*Results reported on 02/28/2017

Figures 2 to 4 show the cumulative bit flips distributions versus test duration obtained for the three experiments. Test has been conducted under nominal operating conditions: V_{DD} = 1.2V, room temperature, standard checkerboard test pattern. These results will serve as raw data for the multi-Poisson process analysis conducted in the next section.

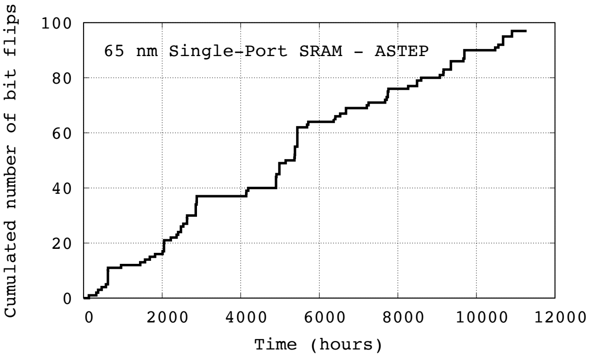

Figure 2. Cumulated distribution of bit flips versus time for the altitude experiment on the ASTEP platform.

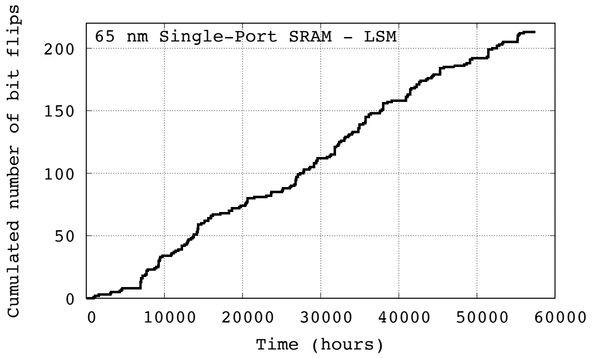

Figure 3. Cumulated distribution of bit flips versus time for the underground experiment at LSM.

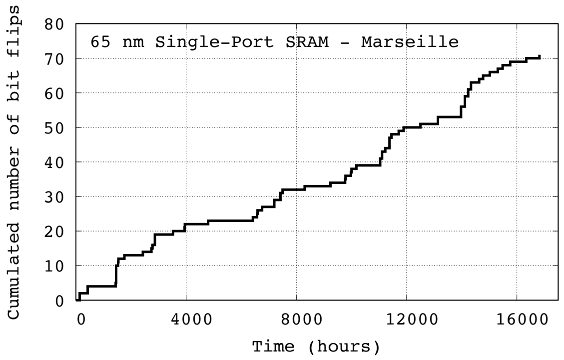

Figure 4. Cumulated distribution of bit flips versus time for the sea-level experiment in Marseille.

4. Results and discussion

From raw data on Figs. 2 to 4 and because the three experiments involved the same quantity of memory (3,226 Mbit), we first extracted in Tables 2 to 4 the event rate per hour (number of events divided by the experiment duration) of single events as a function of the event multiplicity (an event of unit multiplicity corresponding to a single bit upset).

Table 2. Event rate extraction from RTSER data for the altitude experiment on ASTEP platform.

Event multiplicity	Number of Events	Event rate (h^{-1})
1	44	$\lambda_1 = 3.90 \times 10^{-3}$
2	7	$\lambda_2 = 6.21 \times 10^{-4}$
3	5	$\lambda_3 = 4.43 \times 10^{-4}$
4	3	$\lambda_4 = 2.66 \times 10^{-4}$
5	1	$\lambda_5 = 8.87 \times 10^{-5}$
6	1	$\lambda_6 = 8.87 \times 10^{-5}$
7	1	$\lambda_7 = 8.87 \times 10^{-5}$

Table 3. Event rate extraction from RTSER data for the underground experiment at LSM.

Event multiplicity	Number of Events	Event rate (h^{-1})
1	109	$\lambda_1 = 1.91 \times 10^{-3}$
2	24	$\lambda_2 = 4.21 \times 10^{-4}$
3	12	$\lambda_3 = 2.10 \times 10^{-4}$
4	2	$\lambda_4 = 3.51 \times 10^{-4}$
5	2	$\lambda_5 = 3.51 \times 10^{-5}$
6	2	$\lambda_6 = 3.51 \times 10^{-5}$
7	0	$\lambda_7 = 0$

Table 4. Event rate extraction from RTSER data for the sea-level experiment at Marseille.

Event multiplicity	Number of Events	Event rate (h^{-1})
1	36	$\lambda_1 = 2.09 \times 10^{-3}$
2	9	$\lambda_2 = 5.22 \times 10^{-4}$
3	4	$\lambda_3 = 2.32 \times 10^{-4}$
4	0	$\lambda_4 = 0$
5	1	$\lambda_5 = 5.80 \times 10^{-5}$
6	0	$\lambda_6 = 0$
7	0	$\lambda_7 = 0$

From Eq. (1) also valid in terms of event rate, one can consider that for a given test location:

$$\lambda_i = AF \times n\text{-}\lambda_i + \alpha\text{-}\lambda_i \qquad (5)$$

where λ_i, n-λ_i and α-λ_i are respectively the total, neutron and alpha event rates for events of multiplicity i (i=1, 2,…).

Considering Eq. (5) for both ASTEP (AF = 6.5) and LSM (AF = 0) experiments, it is then possible to extract these n-λ_i and α-λ_I values for the 3,226 Mbit of tested devices. This extraction is reported in Table 5 and illustrated in Fig. 4. These results show that, for this particular bulk 65nm technology, soft errors are dominated by the contribution of alpha-particle radioactivity present in IC materials up to events of multiplicity equal to 6. In particular, the alpha event rate is 6 times larger than neutron event for SBU, 7 times larger for MCU(2), 5 times larger for MCU(3) and 4 times larger for MCU(5) and MCU(6). Neutrons and alphas have finally similar event rate for MCU(4) whereas neutrons seems to dominate for larger MCUs.

In order to verify the validity of such extractions, we use on more time Eq. (5) to estimate the alpha and neutron event rates for Marseille location from data of Table 5 extracted by the combination of ASTEP and LSM results. Taking AF = 0.9 for Marseille, Table 6 shows the results of the so-called "predicted" event rates using this procedure. These values are compared to the experimental (i.e. measured) event rates and are used to "predict" the number of events vs. multiplicity for a fixed duration of 17,233 h corresponding to the measurements. Table 5 shows that these predicted values are very close to the measured ones, demonstrating here the interest of such a multi-Poisson process analysis to calculate not only the global event rate of the circuits but also to quantify the respective contributions of MCU events as a function of event multiplicity. In the conference presentation and in the final paper, a similar analysis will be applied to bulk 40nm SRAMs for which results extracted from altitude and sea-level experiments [8] will show more contrasted results between neutron and alpha contributions to MCU events with multiplicities ranging up to 22.

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Table 5. Extracted values of neutron and alpha event rates from data of Tables 2 and 3 using Eq. (5).

Event multiplicity	**Neutron event rate (h^{-1})**	**Alpha event rate (h^{-1})**
1	n-$\lambda_1 = 3.06\times10^{-4}$	α-$\lambda_1 = 1.91\times10^{-3}$
2	n-$\lambda_2 = 3.08\times10^{-5}$	α-$\lambda_2 = 3.33\times10^{-4}$
3	n-$\lambda_3 = 3.59\times10^{-5}$	α-$\lambda_3 = 2.10\times10^{-4}$
4	n-$\lambda_4 = 3.55\times10^{-5}$	α-$\lambda_4 = 3.51\times10^{-5}$
5	n-$\lambda_5 = 8.25\times10^{-6}$	α-$\lambda_5 = 3.51\times10^{-5}$
6	n-$\lambda_6 = 8.25\times10^{-6}$	α-$\lambda_6 = 3.51\times10^{-5}$
7	n-$\lambda_7 = 1.36\times10^{-5}$	α-$\lambda_7 = 0$

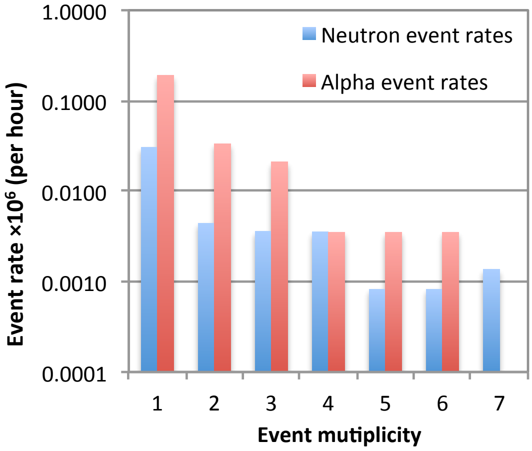

Figure 4. Neutron and alpha event rates as a function of event multiplicity as extracted in Table 5.

Table 6. Event rate extraction from RTSER data for the sea-level experiment at Marseille.

Event multi-plicity	**Number of Events**		**Event rate (h^{-1})**	
	Measured	Predicted	Measured	Predicted
1	36	38	2.09×10^{-3}	2.18×10^{-3}
2	9	6	5.22×10^{-4}	3.72×10^{-4}
3	4	4	2.32×10^{-4}	2.42×10^{-4}
4	0	1	0	6.67×10^{-5}
5	1	1	5.80×10^{-5}	4.24×10^{-5}
6	0	1	0	4.24×10^{-5}
7	0	0	0	1.21×10^{-5}
TOTAL	50	51		