Study of the Effects of MBUs on the Reliability of a 150 nm SRAM Device

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ABSTRACT

Soft errors induced by radiation are an increasing problem in the microelectronic field. Although traditional models estimate the reliability of memories suffering Single Event Upsets (SEUs), Multiple Bit Upsets (MBUs) are becoming more and more important as technology scales. In this paper, a model that deals with MBUs in memory systems, which allows calculating reliability in a fast way similar to the SEU case, has been used to analyze the Mean Time To Failure (MTTF) of a 150 nm device under radiation. This analysis illustrates the importance that physical factors, as the energy, have on the system reliability.

Categories and Subject Descriptors

B.8.1 [**Performance and Reliability**]: Reliability, Testing, and Fault-Tolerance.

General Terms

Reliability.

Keywords

Multiple Bit Upsets (MBUs), reliability, memory, radiation.

1. INTRODUCTION

Memories are used in most digital systems. From generic computers to specific embedded applications and FPGAs, all need storage devices with an increasing capacity. Therefore, from a practical point of view, the reliability of memories is important in order to guarantee the correct operation of the system [1][2]. This has led to several studies [3][4] that discuss various reliability models.

Although reliability has been studied from long ago [5], new sources of errors are arising, apart from the traditional ones, what makes the probability of failure increasingly higher. This is particularly visible in hostile environments where there are physical phenomena that affect semiconductors in a negative way. Radiation [6] is one of these factors and its influence in errors has been reported many times [7]. Due to this, memories are usually protected, in order to make them as much fault tolerant as possible. One of the most used mechanisms is single error correction and double error detection codes (SEC-DED) [8]. These codes add a level of redundancy at the expense of using some of the memory capacity to store the extra information needed for error detection and correction. In this way, isolated Single Event Upsets (SEUs) [9][10], which produce a single error in a given memory word, can be automatically corrected, as long as no more than one affects the same memory word at the same time. The correction is achieved with the so-called scrubbing mechanism. Through this, a scrubbing period is defined, t_s, which triggers a rewrite process in the memory, updating the wrong words with their right values (using the SEC codes).

However, it is possible that two (or more) independent SEUs can strike on the same word within the same scrubbing period. If this happens, the errors would be uncorrectable, leading to a failure of the system. Many models are described in the literature that address this scenario and calculate the Mean Time to Failure (*MTTF*) and reliability of the system [3][4].

However, there are other phenomena that do not induce a SEU in the system, but multiple simultaneous errors, what is known as Multiple Bit Upsets (MBUs) [11]. This may happen, for example, when a highly charged particle strikes on the device, and due to its energy or incidence angle, it affects not only an isolated transistor but a larger area, disturbing several memory cells. As the integration level grows, these memory cells become smaller, and the probability of MBUs increases. The importance of MBUs has been recently addressed in several papers [11][12], concluding that a growing number of errors are due to this fact.

One of the most direct mechanisms to mitigate the effect of MBUs is the use of an interleaving scheme. This mechanism spreads the bits in a logical word into different physical words, following a constant pattern (i.e. all the bits in the logical word are separated by a fixed pattern). Therefore, the bits physically close belong to different logical words, and since MBUs affect a reduced area in the memory, the induced errors would be correctable by the SEC codes. However, MBUs can produce failures, and therefore have an effect on the reliability of the system, what has been proved by recent studies. An SEU followed by an MBU (or vice versa) or a combination of MBUs, may produce double errors in the same logical word, leading to the failure of the system [11].

Although some works have been done in order to characterize the effects of MBUs in memories from a physical point of view (see [13][14] for an analysis of error patterns and effects), no mathematical model has been used to evaluate their reliability. A model has been recently proposed in [15], which will be used in

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this paper to perform a detailed analysis of how MBUs affect the system. In section 2, the model that deals with these effects is introduced; in section 3, several results using experimental data are offered; finally, some conclusions are discussed in section 4.

2. MODELING THE EFFECTS OF MULTIPLE BIT UPSETS

As mentioned before, there are many models that take SEUs into account, but none of them studies the effect of MBUs from a mathematical point of view, in part due to the complexity of the derivations. However, the importance of MBUs is increasing for each new technology node, and therefore they have to be considered when calculating the reliability of the system.

In this way, we propose a theorem that, analyzing the simpler SEU case, provides a lower bound for the reliability of the MBU scenario. Due to the space limitation, only the case of non-scrubbing will be developed in this paper, but a similar derivation can be performed when scrubbing is used (see [15]). Before the theorem is presented, the assumptions considered for its derivation will be explained.

2.1 Assumptions

The following assumptions are similar to other models in the literature, and therefore are representative of the problem environment.

- Single Error Correction (SEC) codes are used to protect memories. This means that an isolated error in a memory word will never produce a failure, since it will be corrected by the protection codes when that word is read.
- Physical interleaving organization is implemented in the memory. The purpose of this is to physically separate the bits that form the same logical word, following a certain pattern. This is important because the errors produced by an MBU tend to be physically close.
- There is a constant event arrival rate for the entire memory, λ. In this case, conversely to what happens in the SEU study, the difference between number of events (g) and number of errors (m) has to be taken into account. It is clear that for SEUs, $g = m$, since there is a univocal relation between both. However, when MBUs are considered, $g < m$. Let us define the errors-per-event set, Q, as:

  $Q = \{q_i \mid i \leq g,\ q_i \geq 1\}$, where q_i is the number of errors produced by event i. All the elements in Q are independent and identically distributed random variables.
- The events that arrive at the system follow a Poissonian distribution. Since an event can produce several errors, a probability distribution function of errors-per-event (that is the distribution for each q_i) has to be defined, P, as:

  $P = \{p(n) \mid n \in \mathrm{N},\ \sum_{n=1}^{\infty} p(n) = 1\}$, where $p(n)$ indicates the probability that a certain event produces n errors.

Following with the last assumption, it can be proven that the number of errors, m, in a given time interval, t, follows a Compound Poisson process [16], where $p(n)$ is the compounding function. The probability of m errors in time t is given by:

$$P(m,t)=\sum_{i=0}^{\infty}\left(\frac{(\lambda\cdot t)^{i}}{i!}\cdot e^{-\lambda\cdot t}\cdot p^{i*}(m)\right) \tag{1}$$

where $p^{i*}(m)$ is the i-fold convolution of $p(n)$.

2.2 MBU vs. SEU scenarios

Although the MBU case could be seen as an extension of the SEU one, it is in fact a more complex scenario. The number of errors per event is not the only effect that happens in the system. If we consider the effect of interleaving, errors physically close will affect memory words logically distant (or in other words, the different errors in the MBU will affect different logical words, and they will not produce a failure thanks to the correction of the SEC codes). In this way, an n-bit MBU will never produce a failure, but n independent SEUs could do so. Intuitively, it can be seen that the number of errors needed to reach a failure will be higher in the MBU case than in the SEU one.

In this subsection, a comparative analysis of these two cases will be offered, putting in perspective the mentioned effect.

Let us consider the probability of m errors in time t, $P(m,t)$. The reliability function $R(t)$ can be defined as follows:

$$R(t)=1-\sum_{m=1}^{\infty}\left(P(m,t)\cdot P_f(m)\right) \tag{2}$$

where $P_f(m)$ is the probability of failing given m errors, and therefore, the term in the summation is the probability that m errors happen in t, and that a failure is produced by those m errors.

Let us explore how P_f should be defined in the current problem. For the sake of simplicity, the case of single error events (SEUs) will be initially considered. Assuming a memory with M words, each of them protected with single error correction codes, then for single error events $P_f(m)$ takes the form:

$$P_f(m)=\sum_{j=1}^{m}\left(\frac{j-1}{M}\cdot\prod_{i=1}^{j-1}\left(1-P_f(i)\right)\right) \qquad P_f(1)=0 \tag{3}$$

The second equation is due to the SEC codes, which make the probability of failure with an isolated error null.

The product term implies the probability that j-1 errors have not produced a failure (since they have affected different memory positions, and therefore corrected by the SEC logic). In the same way, (j-1 / M) denotes the probability that the j-th error strikes on one of the j-1 (out of M) previously affected memory positions, therefore producing a failure.

Unfortunately, in the case of MBUs, following a per-event distribution $p(n)$ makes the derivation of $P_f(m)$ complex, as the errors within each event are assumed (by using interleaving) to fall on different words. To see this complexity, let us examine an example where $p(n)$ = 1 for n = 2, and 0 elsewhere (each event produces 2 errors always):

$$P_f(m)=\sum_{j=1}^{m}\left(\frac{j'-1}{M}\cdot\prod_{i=1}^{j-1}\left(1-P_f(i)\right)\right) \tag{4}$$

where j' equals j for j odd and j-1 for j even.

In this case, what distorts the results of expression (3) is the effect mentioned before. The first two errors (produced both by the first event) can never produce a failure, because according to the assumptions they will be physically close but logically distant. Therefore no failure may happen until the third error arrives (which is the first of the second event) and eventually strikes on the same word as the first or second error did. A similar situation happens with the fourth error, where a failure can occur together with the first or second error, but never with the third one (both produced by the second event). Through this example, it can be seen that the probabilities of failure are affected by how errors are distributed within MBUs, or in other words, by $p(n)$.

For an arbitrary distribution $p(n)$, the computation of $P_f(m)$ becomes even more complex. However, from the example above it can be seen that, given a certain number of errors m, the probability of failure $P_f(m)$ in the case these errors come grouped in MBUs is always lower than if they come distributed as individual SEUs. This is due to the constraint explained before by which all the errors forming the same MBU cannot produce a failure by themselves, and therefore the combinations that lead to a failure are lower. With this consideration, the single error event case is an upper bound for the more general MBU case.

$$P_f(m)\big|_{MBU} \le P_f(m)\big|_{SEU} = \sum_{j=1}^{m}\left(\frac{j-1}{M}\cdot\prod_{i=1}^{j-1}\left(1-P_f(i)\right)\right) \tag{5}$$

Likewise, the reliability function can be lower bounded as

$$R(t)\big|_{MBU} \ge 1-\sum_{m=1}^{\infty}\left(P(m,t)\cdot\sum_{j=1}^{m}\left(\frac{j-1}{M}\cdot\prod_{i=1}^{j-1}\left(1-P_f(i)\right)\right)\right) \tag{6}$$

where the $P_f(m)$ associated to the single error event case is used in the right term. The MTTF can also be lower bounded as

$$\begin{aligned} &MTTF\big|_{MBU} = \int_0^{\infty} R(t)\cdot dt \ge \\ &\int_0^{\infty}\left\{1-\sum_{m=1}^{\infty}\left(P(m,t)\cdot\sum_{j=1}^{m}\left(\frac{j-1}{M}\cdot\prod_{i=1}^{j-1}\left(1-P_f(i)\right)\right)\right)\right\}\cdot dt \end{aligned} \tag{7}$$

Since the previous expressions can become quite complex, a theorem will be presented next that introduces another upper bound approximation, in order to simplify calculations.

2.3 Theorem

Given a memory under the effects of MBUs with a certain arrival rate, λ, and the distribution of errors per event, p(n), the reliability (MTTF) of the system can be lower-bounded considering that the memory is only affected by SEUs with an increased arrival rate λ':

$$MTTF\big|_{MBU}^{\lambda} \ge MTTF\big|_{SEU}^{\lambda'} \tag{8}$$

This implies that a memory where MBUs are induced with a certain arrival rate λ will be at least as reliable as the same memory where SEUs are induced, but with a higher arrival rate, λ'.

Next, the proof of this theorem will be discussed, as well as the right value of λ' to meet expression (8).

2.3.1 Proof

Let us define m as the random variable that denotes the number of errors producing a memory failure. Let us also define the random variable m_{ac} as the number of errors present in the system when a failure happens. For the case of SEUs only, m_{ac} and m are obviously the same variable. In the case of MBUs the following relationship between them holds:

$$m \le m_{ac} \tag{9}$$

This is due to the fact that errors come grouped into MBUs, e.g., if 3 errors are to produce a failure and the first MBUs to arrive happen to induce 2 errors each, then 2 MBUs will be needed to reach the 3 overall errors (m=3), but in fact 4 errors (m_{ac}=4) will have occurred in the system (2 errors after the first MBU and 4 after the second one; the value of 3 cannot be directly reached). Let us define the random variable g as the number of events to failure. Since these g events have produced all the errors in the system until it fails, then m_{ac} can be written as:

$$m_{ac} = \sum_{i=1}^{g} q_i \tag{10}$$

where q_i are the independent random variables defined before. Taking the mathematical expectation on (10), the following is obtained:

$$E[m_{ac}] = E\left[\sum_{i=1}^{g} q_i\right] \tag{11}$$

Applying Wald's identity (since q_i are independent and identically distributed) to the rightmost member of (11), the following expression is obtained:

$$E\left[\sum_{i=1}^{g} q_i\right] = E[g]\cdot E[q_i] \tag{12}$$

Let us define $Q_{\substack{per\\event}}$ as the expected value of distribution q_i, what is determined by $p(n)$ in the following way:

$$Q_{\substack{per\\event}} = E[q_i] = \sum_{j=1}^{\infty} j\cdot p(j) = 1+\sum_{j=2}^{\infty}(j-1)\cdot p(j) \tag{13}$$

Then, combining (11) and (12):

$$E[m_{ac}] = E\left[\sum_{i=1}^{g} q_i\right] = Q_{\substack{per\\event}}\cdot E[g] \tag{14}$$

Now, considering the inequality (9) and (14):

$$E[m] \le Q_{\substack{per\\event}}\cdot E[g] \tag{15}$$

Or, in other words,

$$E[g] \ge \frac{E[m]}{Q_{\substack{per\\event}}} \tag{16}$$

Let us consider now the well-known relationship of the Mean Time To Failure (*MTTF*) and Mean Events To Failure (*METF*) for Poisson distributions [3] (see [15] for demonstration that it also applies for the current case of Compound Poisson):

$$MTTF = \frac{METF}{\lambda} \tag{17}$$

As seen in expression (16), for the MBU case, the expected value of the number of events to failure, $E[g]$ is always higher or equal than $E[m]\,/\,Q_{\substack{per\\event}}$. However, $E[g]$ is, by definition, the *METF*.

Therefore, combining (16) and (17),

$$MTTF\Big|_{MBU}^{\lambda} \geq \frac{E[m]\big|_{MBU}}{\lambda \cdot Q_{\substack{per\\event}}} \geq \frac{E[m]\big|_{SEU}}{\lambda \cdot Q_{\substack{per\\event}}} \tag{18}$$

where the rightmost inequality in (18) stems from $P_f(m)$ being lower in the MBU case as discussed before.

But for single error events, the number of events is identical to the number of errors (one error per event), and therefore, $E[m]$ is the definition of *METF* for the SEU case. In this way,

$$\frac{E[m]\big|_{SEU}}{\lambda \cdot Q_{\substack{per\\event}}} = \frac{METF\big|_{SEU}}{\lambda'} = MTTF\Big|_{SEU}^{\lambda'} \tag{19}$$

where λ' is defined as

$$\lambda' = \lambda \cdot Q_{\substack{per\\event}} = \lambda \cdot \left[1 + \sum_{j=2}^{\infty} (j-1) \cdot p(j)\right] \tag{20}$$

Expression (19) represents the *MTTF* for single error events, with a modified event arrival rate, λ'.

Therefore, through (18) and (19), the inequality (8) is obtained:

$$MTTF\Big|_{MBU}^{\lambda} \geq MTTF\Big|_{SEU}^{\lambda'}$$

2.4 Effect of the theorem on the reliability calculation

What expression (8) means is that, in order to study the reliability of a memory affected by MBUs, the simpler case of single error events can be studied instead, with λ increased in the factor mentioned in (20). The results obtained can be extrapolated to the MBU as a lower bound of the *MTTF*, what simplifies the process compared to the calculation given by (7).

This is an important result, since this lower bound (the *MTTF* for the SEU case) can be easily calculated, and therefore the application of (8) is straightforward. For example, for large values of *M*, the approximation (21) presented in [17] could be used to quickly evaluate the lower bound:

$$MTTF\Big|_{SEU}^{\lambda'} \cong \frac{1}{\lambda'} \cdot \sqrt{\frac{\pi}{2} \cdot M} \tag{21}$$

As a summary of the present section, it has been shown that the *MTTF* in the case of MBUs can be lower bounded with the SEUs only case based on two observations: 1) The errors within an MBU can not occur on the same word and 2) The number of errors present in the system (m_{ac}) when a failure happens on error *m* is larger in the MBU case, as the errors arrive in groups.

Another important point is that as *M* grows (size memory), the approximation in (8) gets better. This is so because in this case, since the probability of failure decreases, most of the failures will occur for large values of *m* such that m/m_{ac} is close to 1 (and therefore expressions (8), (9) and (16) tend to become identities).

3. SIMULATION RESULTS

The use of the model enables the analysis of reliability utilizing available data from real radiation experiments. A set of simulations has been conducted on a memory system as the one described in [11]. The memory is a 150 nm technology 1.8 V 6T SRAM device. The experiments reported in [11] were performed at a neutron facility, with four different beam energies: 22 MeV, 47 MeV, 95 MeV and 144 MeV.

For each of these energies, the distribution function of errors-per-event, *p*(*n*) can be derived from the provided results, as shown in Table 1.

Table 1. Distribution of errors per MBU in the experiment

	p(1)	p(2)	p(3)	p(4)	p(5)
22 MeV	0.730	0.200	0.050	0.015	0.005
47 MeV	0.645	0.230	0.090	0.025	0.010
95 MeV	0.575	0.230	0.120	0.050	0.025
144 MeV	0.530	0.250	0.130	0.060	0.030

The values of p(6) and higher are ignored, due to their low relative weight (under 1%). A value of $\lambda = 0.1$ per word has been selected for the simulation. However, since the analysis focuses on reliability ratios, the results can be extrapolated to other arrival rates. It should be noted that λ will be taken as a constant for the sake of simplicity, but in fact it is also a function of the energy (a higher energy would produce a higher percentage of particles that cause errors).

The calculation of the *MTTF* for the previous scenarios has been performed. First, the proposed theorem has been applied, and then it has been contrasted with the results from two types of simulations. The obtained information is listed on Tables 2, 3, 4 and 5 in the following way:

- SEUs only with increased rate (theorem). This corresponds to the *MTTF* calculated using the SEU model (expression (21)), with λ increased as per (20). This should be a worst case (lower bound) for the *MTTF*.
- MBU independent errors (simulation). The errors in an MBU may affect any logical word, since they are considered to be independent. Therefore, they could affect the same logical word. This scenario models observation 2) of subsection 2.4., but not 1).
- MBU errors on different registers but not independent. The errors in an MBU affect different logical words (due to the effect of interleaving). This means that they are randomly distributed, but no more than one error per MBU can affect the same logical word. This scenario models both observations 1) and 2) of subsection 2.4.

The results are the average of 300,000 simulations. Table 2 shows the results for the case of 22 MeV, Table 3 for 47 MeV, Table 4 for 95 MeV and Table 5 for 144 MeV, considering different sizes (*M*) of the memory.

The first consideration is that the *MTTF* values obtained through the presented method (second column) is always a worst case (lower bound) of the simulation results (third and fourth columns). This can be applied to all the explored energies. This is in line with the expected behavior explained in previous sections. In other words, the reliability of the memory under MBUs can be characterized by using the much simpler SEU model, with an increased event arrival rate. The second consideration is that the difference between the predicted *MTTF* using the theorem and the results given by the simulation decreases as the memory size grows. This means that the predictions are more accurate for larger sizes, which in fact is the actual scenario for real memories.

Table 2. MTTF (in seconds) vs. memory size for 22 MeV

$\log_2$ M	SEUs with λ’	MBUs (independent)	MBUs (non-independent)
5	1.6231	1.8581	1.9288
7	0.8116	0.8712	0.8904
9	0.4058	0.4209	0.4260
11	0.2029	0.2064	0.2077
13	0.1014	0.1023	0.1026
15	0.0507	0.0509	0.0510

Table 3. MTTF (in seconds) vs. memory size for 47 MeV

$\log_2$ M	SEUs with λ’	MBUs (independent)	MBUs (non-independent)
5	1.4528	1.6973	1.7818
7	0.7264	0.7845	0.8083
9	0.3632	0.3779	0.0384
11	0.1816	0.1858	0.1869
13	0.0908	0.0918	0.0920
15	0.0454	0.0456	0.0458

Table 4. MTTF (in seconds) vs. memory size for 95 MeV

$\log_2$ M	SEUs with λ’	MBUs (independent)	MBUs (non-independent)
5	1.2881	1.5349	1.6351
7	0.6441	0.7045	0.7331
9	0.3220	0.3372	0.3446
11	0.1610	0.1649	0.1669
13	0.0805	0.0814	0.0819
15	0.0403	0.0405	0.0406

Table 5. MTTF (in seconds) vs. memory size for 144 MeV

$\log_2$ M	SEUs with λ’	MBUs (independent)	MBUs (non-independent)
5	1.2241	1.4675	1.5710
7	0.6120	0.6720	0.7005
9	0.3060	0.3212	0.3283
11	0.1530	0.1570	0.1586
13	0.0765	0.0774	0.0780
15	0.0383	0.0385	0.0387

This is better seen through a graph. Figure 1 depicts results for 22 MeV in Table 2 (the rest of the energies offer a similar trend). The predicted values and the two simulation results converge to the same *MTTF*. Another conclusion is that the *MTTF* of MBUs with independent errors is always lower than the non-independent case. This happens because the former does not model observation 1) of subsection 2.4., as mentioned before.

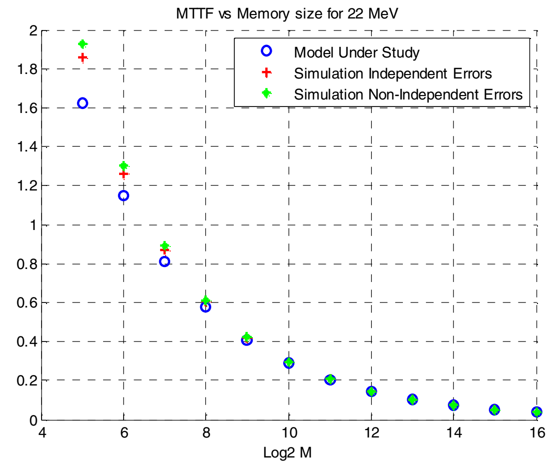

Figure 1. ***MTTF*** **of the memory predicted with the proposed method and calculated with simulations (for 22 MeV and different sizes).**

Once the quality of the method has been put in perspective, the next step is to study how *λ’* varies with energy. As energy grows, it seems intuitive that more errors due to MBUs are to be produced, thus reducing the *MTTF* of the memory. It is also intuitive that more energetic MBUs would have to be emulated through the SEU case with higher arrival rates. In other words, the increasing energy that affects the memory is modeled with the arrival of a larger number of standard-energy particles.

Using again the experimental data in Table 1, the increment in the arrival rate, λ’/λ, (or in other words $Q_{\substack{per\\event}}$ as per expression (20)) has been calculated. Results are shown in Figure 2.

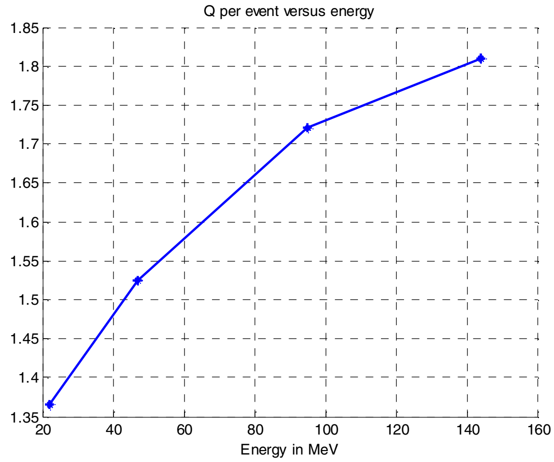

Figure 2. Evolution of $Q_{\substack{per\\event}}$ = λ’/λ with the energy.

The first conclusion is that the increment in the arrival rate grows with the energy, as expected. This clearly models the arrival of more energetic particles in the system.

The second conclusion is that this growth is not linear, but it seems to be logarithmic. This means that the system saturates at a certain energy threshold and increasing its level would not produce more errors. The consequence of this is that the *MTTF* of the memory decreases with energy, but tends to a certain level, as shown in Figure 3.

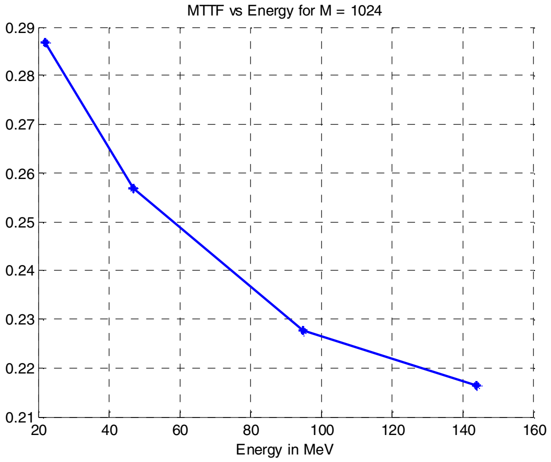

Figure 3. Evolution of the *MTTF* with the energy, for M = 1024.

It is seen that reliability does not decrease linearly, and tends to an asymptotic value. It is important to notice that this model characterizes the effect of soft errors with energy. If energy keeps growing after the saturation point is reached, other phenomena might appear that would affect the memory, thus reducing its reliability. The study of these effects other than soft errors is out of the scope of this paper.

4. CONCLUSIONS AND FUTURE WORK

In this paper, it has been proved that the analysis of MBUs on a memory system can be simplified with the study of SEUs, adjusting the event arrival rate to make both cases comparable. Thanks to this approach, the complex calculations intrinsic to the MBU case are avoided, what gives a faster way to find out the reliability of the system.

The model has been used to study the reliability of a memory affected by different energy levels. This case study was reported in [11], and consisted in radiating a 150 nm technology 1.8 V 6T SRAM device at a neutron facility, with several beam energies.

Two main conclusions have been extracted from the experimental work:

- Modeling MBUs with SEUs arriving at a higher rate offers accurate results, and more so when the memory size is larger.
- The reliability of the memory decreases with higher energy levels, but not linearly. This might imply that other phenomena (rather than soft errors) would have a larger influence in the system when a certain energy threshold is reached.

As a future work, similar studies to the one performed for energy would be conducted, this time for other physical parameters, as the angle of incidence or the type of particle. In this way, the effect of these parameters on the reliability can be analyzed by modeling them with the equivalent SEU scenario and the appropriate λ'.

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