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Compact model for fast analytical evaluation of soft error rate in highly scaled memory circuits in space environment

Abstract. *It is shown that traditional analytical formula for soft error rate estimation (figure-of-merit) in digital memories in space environment can lead to large uncertainties. An alternative approach, based on another representation of experimental data, has been proposed.*

Streszczenie. *Przedstawiono, że tradycyjna formuła analityczna do szacowania stopnia miękiego błędu (współczynnik jakości) w pamięci cyfrowej w przestrzeni kosmicznej może prowadzić do dużych niepewności. Zaproponowano alternatywne podejście, oparte na innych danych eksperymentalnych. kompaktowy model do szybkiej oceny analitycznej miękkie stopy błędu w bardzo skalowane układów pamięci w przestrzeni kosmicznej.* ***(Kompaktowy model do szybkiej oceny analitycznej stopnia miękkiego błędu w wysoko przeskalowanych układach pamięci w przestrzeni kosmicznej)****.*

Keywords: Figure-of-merit, single event upset, soft error rate, multiple cell upset.
Słowa kluczowe: Współczynnik jakości, pojedyncze zakłócenie, stopień miękkiego błędu, wielokomórkowe zakłócenie.

Introduction

Modern highly scaled memory circuits have an area less than 1 um^2 and critical charge less than 1 fC. That's why for modern memory circuits with technological standards less than 100nm major problem in space is the multiple cell upsets (MCUs) that is getting own heavy ionizing particle switch more than own memory cell. This circumstance causes a necessity of the Error Correction Codes (ECCs) application that, in its turn, leads to a decrease in functional performance [1]. To optimize the ECC algorithms it's necessary to use an analytical compact model to estimate the soft error rate (SER) calculation in space because the calculation of the exact numerical solution requires a lot of time. Soft error rate calculation is made without taking into account error correction code, since it will be selected after analysis of results. "Figure-of-Merit" (FOM) introduced in 1983 [2] is one of the possible approaches. But this method is based on not well-defined parameters in modern circuits as will be shown in this paper.

The low values of the critical charge of the cell leads to the very low values of the critical Linear Energy Transfer (LET) (often less than 1 MeV-cm^2/mg). This means that the above-threshold portion of the cross section vs LET curve takes up almost the entire range of measured values. Moreover, the cross section vs LET dependence has not the saturation portion remaining LET increasing function over the entire range of measurements. In this paper, we show that this kind of behaviour associated with multiplicity failure of one ionizing particle. Generally speaking, there are no physical reasons for failures sectional obliged satisfied, except that a section of physical failures cannot be larger than the total area of all cells in the circuit. The only reason for the saturation in low integration memory circuits is local impact when one ion cannot hit more than one memory. Indeed, when the local character of the impact of increasing energy above the threshold have come to nothing lead, which corresponds to the saturation. But this argument does not work for highly integrated circuits, when the ionization of a single particle covers several memory cells, which corresponds to the non-local nature of the exposure. When we have nonlocal effects of the energy, spread across multiple cells, the amount of downed cell is proportional to the energy, i.e., actually dose. The paper shows that there is almost a linear dependence of the average cross section of the LET is a reflection of the linear dependence of the number of crashes on the dose.

We propose a new formula for FOM based on quasi-linear approximation of cross-section vs LET dependence [3]. This method has parameters which can be defined much more accurate.

Figure-of-merit

The dependence of the single event upsets cross-section vs LET is traditionally approximated by the Weibull function [4]

$$\sigma = \sigma_{SAT} \begin{cases} 1 - \exp\left[-\left(\dfrac{\Lambda - \Lambda_C}{W} \right)^s \right], & \Lambda > \Lambda_C; \\ 0, & \Lambda \le \Lambda_C, \end{cases} \tag{1}$$

where σ_{SAT} is the saturated value of cross-section, Λ_C is the critical value (threshold) of LET, W is width parameter, s is shape parameter. Soft error rate can be computed using an integral convolution of the cross-section vs LET dependence and the LET flux spectrum $\phi(\Lambda)$ of heavy ions in space environment

$$SER = \int_0^\infty \sigma(\Lambda)\phi(\Lambda)\,d\Lambda, \tag{2}$$

where SER is soft error rate, Λ is Linear Energy Transfer (LET), $\sigma(\Lambda)$ is the LET dependent soft error cross section. This formula requires a numerical integration. Therefore, in practice is often used some simplified approaches, e.g. the figure-of-merit approach, proposed by Petersen in 1983 [2]:

The Petersen approach is based on the two main assumptions

1. The cross-section vs LET dependence is assumed to be a step function $\Theta(x)$

$$\sigma(\Lambda) = \sigma_{SAT}\theta(\Lambda - \Lambda_C). \tag{3}$$

where σ_{SAT} is a saturated value of soft error cross-section, Λ is LET, Λ_C is the critical value (threshold) of LET

2. The differential LET spectrum is assumed to be a power function in the range 2 < LET < 30 MeV cm^2/mg

$$\phi(\Lambda) \cong b/\Lambda^3, \tag{4}$$

where b is an orbit specific rate coefficient with units of upsets/bits-day which can be found in regulations. Then the soft error rate can be estimated as follows

(5)
$$SER = \int_0^\infty \sigma(\Lambda)\phi(\Lambda)\,d\Lambda \cong b\sigma_{SAT}\int_{\Lambda_C}^\infty \Lambda^{-3}d\Lambda = $$
$$= 0.5\sigma_{SAT}\,b/\Lambda_C^2 = \sigma_{SAT}\Phi(\Lambda > \Lambda_C),$$

where $\Phi(\Lambda > \Lambda_C) = 0.5b/\Lambda_C^2$ is the integral ion flux with the LET more than a critical value Λ_C.

Due to the fact that the large values of the Weibull parameter W is typical in the modern memory circuits, the large error arises after a usage of the step function approximation. To reduce this error, Petersen modified the FOM formula as follows [5]

(6)
$$SER \cong \frac{0.5\,b\,\sigma_{SAT}}{\left(\Lambda_C + W\times 0.288^{1/s}\right)^2},$$

where for cross-section vs LET dependence is describe by Weibull function, W is width parameter of Weibull function, s is shape parameter of Weibull function, σ_{SAT} is saturation of soft error cross-section, $\sigma(\Lambda_C + W\times 0.288^{1/s}) = 0.25\sigma_{SAT}$.

Uncertainty of parameters

A lack of saturation in the cross-section vs LET curve in modern memory circuits (with feature size less than 100 nm) up to 120 Mev cm^2/mg has been reported [6]. Both equations (5) and (6) are essentially based on numerical value of the saturation cross-section σ_{SAT}. It is important, this parameter is determined asymptotically with a huge error and it basically depends on the maximum LET used in the experiment.

An example for two Weibull approximations with different order of magnitude σ_{SAT} of the same experimental data [3] is shown on Fig. 1. Both the Weibull approximations formally well describe the experimental data points.

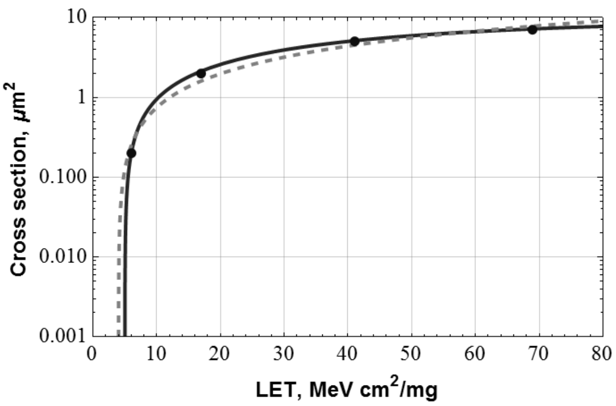

Fig.1. Two Weibull approximation to the same data. Parameters: (dashed) σ_{SAT} = 100 um^2, Λ_C = 4 MeV cm^2/mg, W = 800 MeV cm^2/mg, s = 1; (solid) σ_{SAT} = 10 um^2, Λ_C = 5 MeV cm^2/mg, W = 50 MeV cm^2/mg, s = 1

Different set of numerical parameters of the Weibull distribution leads to large uncertainty in determining of the soft error rate through equations (5) and (6).

Logarithmic form of cross-section vs LET dependence

Above threshold region of the cross-section curve can be interpolated approximately by a linear dependence. It was shown in [3] that it is a direct consequence of multiple cell upsets in highly scaled memories. In reference [3] it has been proposed new analytical form of cross-section vs LET dependence

(7)
$$\sigma(\Lambda) = K_d W \ln\left[1+\exp\left(\frac{\Lambda-\Lambda_C}{W}\right)\right],$$

where K_d is a slope of quasi-linear above threshold region, W is subthreshold logarithmic slope, Λ_C is threshold LET. Equation (7) has not such a poorly defined parameter as a saturation cross-section σ_{SAT}, which cannot be directly determined from the experiment. There are two asymptotic form of equation (6) linear dependence for the above-threshold region ($\Lambda > \Lambda_C$) and exponential dependence for subthreshold ($\Lambda < \Lambda_C$) region

(8)
$$\sigma(\Lambda) \cong \begin{cases} K_d(\Lambda-\Lambda_C), & \Lambda > \Lambda_C, \\ K_d W \exp\left(\dfrac{\Lambda-\Lambda_C}{W}\right), & \Lambda < \Lambda_C. \end{cases}$$

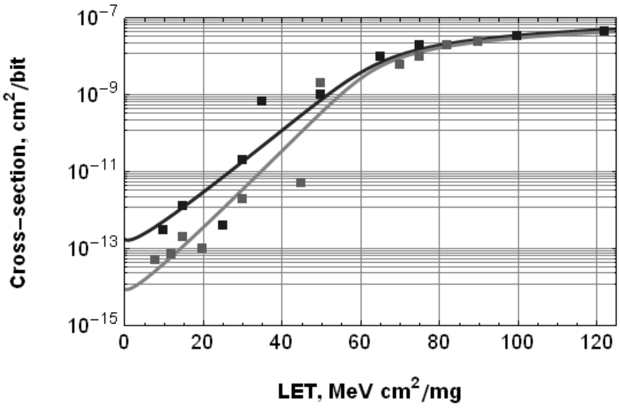

Fig.2. Approximation of experiment data points for perpendicular hits and angled hits [7]. They differ by only own parameter W = 4.1 and 5.0 MeV cm^2/mg of equation (7). Other parameters are the same for both angled hits and perpendicular hits. K_d = 0.53 um^2/(MeV cm^2/mg), Λ_C = 50 MeV cm^2/mg.

As it shown in Fig. 2, the equation (7) can describe all of experimentation data points from [7]. Parameter W of equation (7) can be used for subthreshold region of cross-section vs LET dependence which ignored by Weibull function.

Sub-linear dependence

Lack of saturation in cross-section up to 120 Mev-cm^2/mg has been reported by many investigators. For example Fig. 3 shows the cross-section in a wide range by LET without saturation. For LET more than 50 MeV cm^2/mg cross-section vs LET dependence becomes sub-linear. For that case equation (7) must be modified:

(9)
$$\sigma(\Lambda) = \eta_{eff}(\Lambda)K_d W \ln\left[1+\exp\left(\frac{\Lambda-\Lambda_C}{W}\right)\right].$$

where η_{eff} is effective charge yield.

The effective charge yield η_{eff} is generally decreased function of injection level, dose rate and LET since it limited by recombination between excess electrons and holes. We model this recombination-limited charge as follows

(10)
$$\eta_{eff}(\Lambda) = \frac{(1+4f)^{1/2}-1}{2f}, \quad f = \frac{\Lambda}{\Lambda_1},$$

where Λ_1 is a fitting constant.

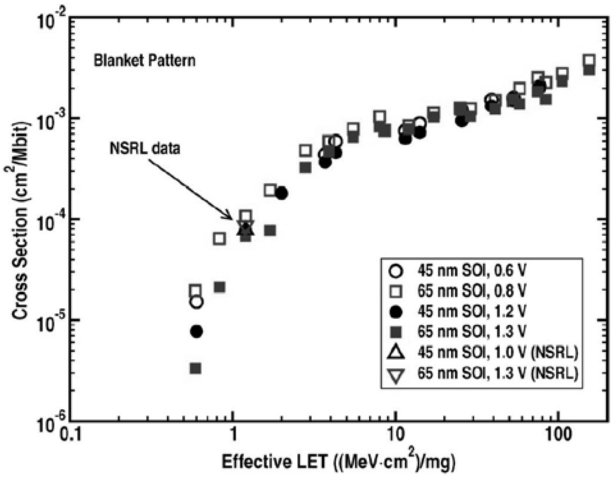

Fig.3. Experimental data points of cross-section in a wide range by LET [6]

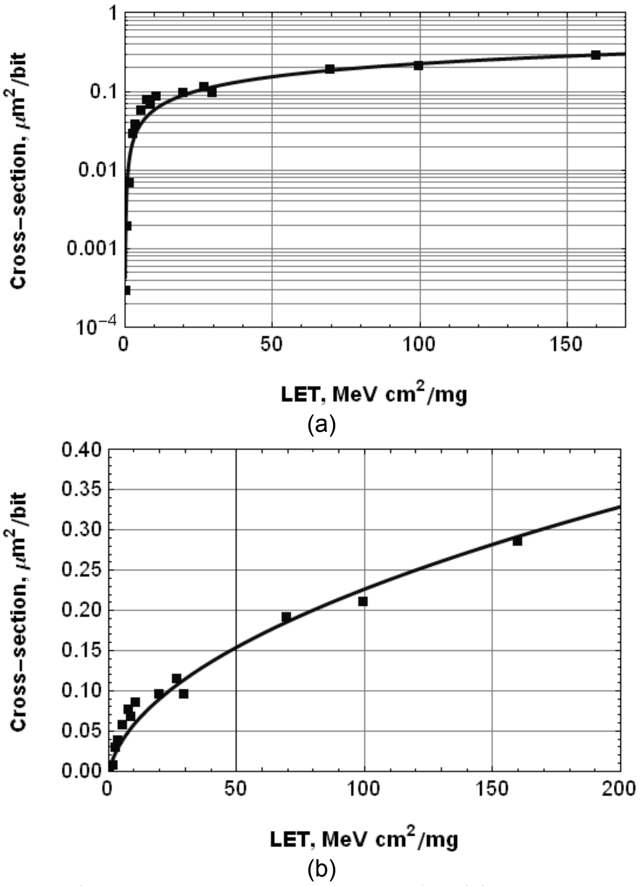

Fig.4. Compare experimental data [6] for SOI 65 nm with approximation by expression (9) a) logarithmic scale; b) linear scale

For low LETs ($\Lambda < \Lambda_1$) the effective charge yield $\eta_{eff} \cong 1$, while for a case large LET ($\Lambda > \Lambda_1$) the charge yield decreases as $\eta_{eff}(\Lambda) \sim \sqrt{\Lambda_1 / \Lambda}$.

Fig. 4 shows a comparison of model (9) with the experimental data points [6]. The logarithmic scaling in Fig 4a stresses the low LET points, while the linear scaling in Fig. 4b emphasizes the high LET points.

Alternative FOM

It was shown in [3] that the above-threshold region of cross-section dependence without saturation can be approximated by a quasi-linear dependence

(11) $$\sigma \cong K_d \left(\Lambda - \Lambda_C \right).$$

Fig 5 shows good agreement of the experimental data points with linear dependence (11) for LET < 70 MeV cm^2/mg.

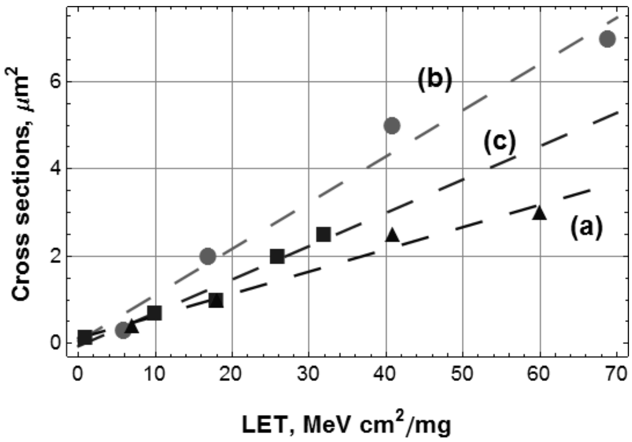

Fig.5. Cross-section vs LET dependencies for different technological standards: (a) 65 nm [8], (b) 90 nm [3], (c) Virtex-5QV [3]

Sub-linear dependence starts at the LET > 50 MeV cm^2/mg. The number of particle with such LET is very low in space. Therefore the approach (11) is accurate enough for space environment. In that way using experimental slope K_d, which can be found directly from the slope of the linear dependence of the cross section on LET, instead of the saturation cross section in the Weibull approximation. Then, the integral (2) yields

(12) $$SER \cong b\frac{K_d}{2\Lambda_C} = b\frac{K_d \Lambda_C}{2\Lambda_C^2} = K_d \Lambda_C \Phi\left(\Lambda > \Lambda_C\right).$$

Expression (12) contains the parameters with an error definition less than 30% in contrast to the parameters in (5) and (6) which may vary several-fold.

Conclusion

It was shown that a usage of the Weibull parameters in simplified analytical estimation of soft error rate in modern memories may lead to significant errors and uncertainties. It has been demonstrated an advantage of the logarithmic interpolation function compared to the Weibull function for description of the upset cross-section vs LET dependence. A new form of figure-of-merit for soft error rate calculation in space environment without uncertainty is proposed.

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