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Statistics and methodology of multiple cell upset characterization under heavy ion irradiation

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ABSTRACT

Mean and partial cross-section concepts and their connections to multiplicity and statistics of multiple cell upsets (MCUs) in highly-scaled digital memories are introduced and discussed. The important role of the experimental determination of the upset statistics is emphasized. It was found that MCU may lead to quasi-linear dependence of cross-sections on linear energy transfer (LET). A new form of function for interpolation of mean cross-section dependences on LET has been proposed.

1. Introduction

As process technology advances into deep nanometer ranges, digital memory reliability becomes a major concern. Highly-scaled digital memories are susceptible to particle-induced single event effect (SEE) because of their low signal charge and noise margin [1]. This circumstance creates new fundamental challenges in terms of modeling, testing, and soft error rate (SER) prediction, including the hadron accelerator environments, which is characterized by a complicated radiation spectrum [2,3]. One of the main concerns is a problem of the multiple cell upsets (MCUs) in highly scaled memory arrays, CPU registers etc., which are defined as simultaneous errors in more than one memory cell induced by a single event. The ratio of the MCUs to the single bit upsets (SBUs) is observed to increase drastically in nano-scaled SRAMs due to physical mechanisms of single-event effects that result in multiple-node charge collection [4]. The total memory area on the chip including intercell regions A_m is a basic layout parameter. Let N_{SBU} is a number of the single bit-flips after irradiation of the chip with heavy ion fluence Φ. Then an experimental condition $N_{SBU}/\Phi A_m \ll 1$ corresponds to the single bit upset mode with dominance of SBU. This inequality means that only a portion of the ions hitting into the memory region area A_m leads to upsets. This allows introducing a concept of a separate sensitive volume followed by a use in standard procedures of soft error rate prediction [5]. An opposite condition $N_{SBU}/\Phi A_m > 1$ becomes typical for modern generations of highly scaled integrated memories. Some problems in a traditional approach in determination of multiple upset cross-sections are noted in [2]. This paper aims at discussing the MCU characterization and its role in dose-like behavior which was found in highly scaled memories under heavy ion irradiation.

2. Physical background

2.1. Primitive cell concept

Memory ICs are organized as rectangular 2D lattices with the “word lines” running horizontally through the rows, and “bit lines” running vertically connecting all cells in that column together. Following this analogy, a primitive memory cell concept can be defined like the primitive cell in the crystals [6]. More specifically, the smallest area in a memory array, which when repeated in two directions without overlapping, reproduces the complete crystal

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without leaving any void will be referred here as the primitive unit cell. A primitive cell may contain in itself one or several bit cells.

It should be noted that the choice of the cell shape is not unique, but the cell area a_{cell} is determined exclusively by the chip layout and it does not depend on the choice of the primitive cell's shape. The density of the primitive unit cells per unit area referring here to as N_m is defined by the relation $N_m a_{cell} = 1$ and it is also independent of choice of the primitive cell.

2.2. Concepts of partial and mean cross-sections for multiple cell upsets

Let us consider a simplest kind of the unit cell containing a single information bit. Generally, every ion hit can lead in highly-scaled memory to occurrence of the n single bit-flips where n are integers taking stochastic values $n=0, 1, 2,\ldots$ Importantly, that a case $n=0$ corresponding to the absence of upsets after ion strike also should be included in mathematical description. We will refer to n as multiplicity of the event. In practice, only the multiplicity mean values are often observed. We found the mean multiplicity concept is closely concerned with the mean upset cross-section concept.

If the total number of bit-flips can be partitioned into the separate event groups with the different multiplicities, the partial cross-section σ_n per a primitive cell for a given multiplicity can be defined as follows:

$$\sigma_n(\Lambda) = \frac{N_\Lambda^{(n)}}{M\,\Phi} \tag{1}$$

where M is the total number of primitive cells, $N_\Lambda^{(n)}$ is a number of events with multiplicity equals n appearing under irradiation of ions with fluence Φ and LET denoting here as Λ.

Using the partial cross-section, the mean cross-sections of multiple upsets can be defined as follows:

$$\langle \sigma(\Lambda) \rangle = \sum n\, \sigma_n(\Lambda). \tag{2}$$

Due to the corresponding points in different unit cells can be considered as equivalent, the cross-sections with different multiplicities are not independent.

It is important that, despite the fact that the partial sections are dependent on the LETs and incident angles, their sum is equal to the area of the unit cell, which is determined only by circuit layout.

$$\sum_{n=0} \sigma_n(\Lambda) = a_{cell}. \tag{3}$$

Eq. (3) will be referred here as completeness condition. This condition has fundamental character, and it is explained by a simple reason that every ion hit into the cell corresponds to a certain value of multiplicity. This circumstance is illustrated schematically in Fig. 1. The form and area of the primitive cell should be determined by careful analysis of the IC technology and layout. In complex circuits it may depend particularly on such details as radiation hardening layout design, position of isolation and node locations. For the sake of simplicity we will analyze here only the simplest case of a single bit cell per the primitive cell.

2.3. Mean multiplicity as mean cross-section

Cross-section of the event is proportional to its probability. Therefore, the experimentally observed distribution of cross-section over multiplicities conforms to the corresponding probability distribution p_n defined as follows:

$$p_n(\Lambda) = \frac{\sigma_n(\Lambda)}{\sum_{n=0} \sigma_n(\Lambda)} = \frac{\sigma_n(\Lambda)}{a_{cell}} \tag{4}$$

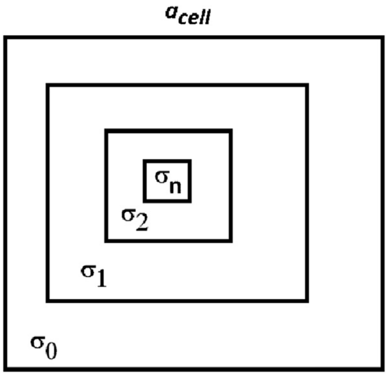

Fig. 1. Primitive cell area can be partitioned into the set of the partial cross-sections. Notice fundamental importance of the "zero multiplicity" σ_0 cross-sections corresponding to the ion hit without any upsets to justify the completeness condition (3).

where the completeness condition (3) is used. Character of the multiplicity distribution is obviously specific for a given ion's LET, incident angle, the chip technology and layout.

Averaging stochastic multiplicity values over this distribution one gets

$$\langle n(\Lambda) \rangle = \sum_{n=0} n\, p_n(\Lambda) = \frac{\sum_{n=0} n\, \sigma_n(\Lambda)}{\sum_{n=0} \sigma_n(\Lambda)} = \frac{\langle \sigma(\Lambda) \rangle}{a_{cell}}. \tag{5}$$

This simple relationship reveals a deep connection between averaged upset cross-section and multiplicity. It means that normalizing the experimental dependence $\langle \sigma(\Lambda) \rangle$ by the characteristic area of the memory layout a_{cell} one can easily gets the dependence of the mean multiplicity as function of incoming ion's LET.

2.4. Example: Application to single bit upsets

Described mathematical formalism is rather general and can be also applied to the results obtained in the low-scaled circuits where the single-bit upsets (SBUs) prevail. The completeness condition in this case takes the form $\sigma_0(\Lambda)+\sigma_1(\Lambda) = a_{cell}$, and the mean multiplicity dependence on LET is expressed as follows:

$$\langle n(\Lambda) \rangle = \frac{\sigma_1(\Lambda)}{a_{cell}} = \frac{\sigma_1(\Lambda)}{\sigma_0(\Lambda)+\sigma_1(\Lambda)} \le 1 \tag{6}$$

where $\sigma_1(\Lambda)$ is a traditional SBU cross-section which is determined with standard procedures. Obviously that σ_0 decreases and σ_1 increases with increasing LET. It is important that due to the completeness condition, the cross-section for the SBU case never exceeds the layout invariant a_{cell} and the mean multiplicity cannot be larger than a unity. This is a direct consequence of single-bit character of the upsets in this case. In practice, due to large inter-cell region area, a part of the ion hits do not cause spin-flips at any LET. Therefore $\sigma_1(\Lambda)$ in the low-scaled ICs typically saturates at a level $\sigma_{SAT} < a_{cell}$ and the mean multiplicity turns out less than a unity in this case $\langle n(\Lambda) \rangle_{SAT} < 1$ (see Fig. 2).

Low-scaled devices correspond to local description when collection charge region is much less than an active area of the memory cell (drain p–n junction, channel etc.). An opposite case of highly-scaled memories corresponds to non-local description when the collection region from a separate ion track covers many memory cells. Nonlocal impact with the multiple cell response leads to good event statistics and may be expressed as dose-like behavior of radiation response.