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Multiple cell upset cross-section modeling: A possible interpretation for the role of the ion energy-loss straggling and Auger recombination

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ABSTRACT

We found that the energy deposition fluctuations in the sensitive volumes may cause the multiple cell upset (MCU) multiplicity scatter in the nanoscale (with feature sizes less than 100 nm) memories. A microdosimetric model of the MCU cross-section dependence on LET is proposed. It was shown that ideally a staircase-shaped cross-section vs LET curve spreads due to the energy-loss straggling impact into a quasi-linear dependence with a slope depending on the memory cell area, the cell critical energy and efficiency of charge collection. This paper also presents a new model of the Auger recombination as a limiting process of the electron–hole charge yield, especially at the high-LET ion impact. A modified form of the MCU cross-section vs LET data interpolation is proposed, discussed and validated.

1. Introduction

Aggressive scaling of the microelectronics components leads to decreased immunity of the digital integrated circuits to external transients due to reducing in noise margin. In particular, the commercial highly-scaled digital memories become extremely susceptible to the single event effects (SEE) because of their low critical charges and small sizes [1]. Scaling has spatial and energetic aspects, namely, the dimensional shrinking and the supply voltage reduction. This leads to several important consequences in the context of susceptibility to ionizing particles. First of all, the size of a memory cell turns out to be less than the lateral dimensions of the heavy ion tracks. Such non-locality manifests itself as the multiple cell upsets (MCUs), which are defined as simultaneous errors in more than one memory cell, induced by a single particle hit [2]. Secondly, due to both scaling and supply voltage lowering, the memory cell critical charge magnitudes Q_C are reducing slowly to the sub-femtocoulomb region. Such values of the collected charge (of order 10^3–10^4 carriers) correspond to the mean deposited energy as small as a few keV and average values of critical linear energy transfer (LET) less than 1 MeV-cm^2/mg [3].

For instance, the critical charges of the SRAM cells fabricated in a 65 nm SOI technology are reportedly estimated between 0.14 fC (or ~880 electrons) and 0.24 fC (or 1500 electrons) [4] corresponding to the critical energies 3.2 keV and 5.4 keV, respectively. An average LET notion is generally assumed to be appropriate for only relatively low-scaled ICs (> 100 nm), having the critical charges > 10 fC [5]. The fact is that an average energy deposition at such low magnitudes turns out to be of the same order as energy-loss fluctuations (straggling) [6]. A role of straggling in single-event effects was discussed also in [7–10]. A physical reason for importance of the straggling in the highly-scaled ICs stems from the fact that typical magnitude of energy transfer in the elementary interaction between ion and electrons (~tens of keV) turns out to be of order or greater than the cell's critical energy.

This means that a soft bit upset could, in principle, be produced by only a single secondary ("delta") electron. A similar effect is likely reported recently in [11], where the "electron-induced SEUs refer to events in which the initiating particle is a high-energy electron (delta-ray); the eventual upsets are produced by thermalized electron–hole pairs generated as the delta-rays lose their energy through ionization."

For low-integrated, circuits we have a rather large critical energy ϵ_C and a bit-flip occurs if only energy deposition is large enough $\langle \Delta E \rangle > \epsilon_C$. For highly-scaled memories, the equality $\langle \Delta E \rangle > \epsilon_C$ may take place even for the extremely low-LET ions such as low-energy proton [12]. The high-LET heavy ions could provide deposit energy (and collected charge amount) sufficient to a multiple cell upset condition $\langle \Delta E \rangle \cong n\epsilon_C$, where n are integers up to

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10–20. At the same time, the energy deposition ΔE is a stochastic variable, fluctuating due to the energy-loss straggling from one ion to another even for the same average LET. We will show in Section 2 that observed multiplicity spread at a given LET can be largely attributed to the energy-loss straggling effects.

We argued in [13] that the average MCU cross-section is approximately proportional to an average multiplicity at a given LET (see Appendix A). It was concluded there that the non-local character of the ion impact leads to approximate proportionality between the average energy deposition (LET) and the average MCU cross-section. A condition $n\varepsilon_C < \Delta E < (n+1)\varepsilon_C$ corresponds to the multiple cell upset case with the multiplicity equal to n. We will show in Section 3 that in an ideal case this corresponds to a staircase-shaped dependence of the MCU cross-section on LET. The role of straggling is that it spreads a staircase-shaped dependence into a quasi-linear one.

In this paper, we argue that, more precisely, the average number of bit-flips per fluence depends not only on the energy deposition and collection efficiency but also on the electron–hole charge yield. The charge yield is typically controlled by the recombination processes. We will show in Section 4 the importance of the Auger recombination for a description of the cross-section shape at high LETs. A physics-based form of the cross-section vs LET interpolation function for a use instead of the Weibull function will be described and discussed in Section 4.

2. Multiplicity distribution as a consequence of energy-loss straggling

The key device characteristic that determines the upset sensitivity of a device is its critical charge QC. This charge is defined as the amount of charge that must be released and collected at the device terminals to cause a single event effect [14]. It is assumed that any excess energy deposition above a critical value ε_C in a sensitive volume leads immediately to a single bit upset occurrence. This is a very strong assumption, being essentially microdosimetric one, suggests a tight coupling between the circuit response and microdosimetry of energy deposition within very small sensitive micro-volumes [15]. Energy deposition is a random variable, and this point is especially noticeable on small spatial scales of modern memory circuits.

The test data are impacted by the variations caused by the ion hit statistics and also by the uncertainties in the ionization and the charge collection processes. Particularly, the energy deposition fluctuations (energy-loss straggling) cause substantial uncertainty in MCU numbers. Indeed, the relative error in number of single bit errors (SBU) can be represented as a sum at least of the two independent terms [13].

$$\frac{\langle \delta N_{SBU}^2 \rangle}{\langle N_{SBU} \rangle^2} = \frac{1}{A_m \Phi} + \frac{\langle \delta n^2 \rangle}{\langle n \rangle^2}, \tag{1}$$

where Φ is the ion fluence, $A_m\Phi$ is a mean number the ion hits into the memory region area A_m. The former term in (1) can be reduced due to good event statistics while the multiplicity variance $\langle \delta n^2 \rangle$ is controlled by the internal mechanisms of energy deposition and charge collection. Note, the second term in (1) is a lack for the single bit upsets. We proposed in [13] that the multiplicity variance is likely caused by fluctuations in energy deposition (energy-loss straggling) during the passage of a single ion and cannot be reduced experimentally

$$\frac{\langle \delta n^2 \rangle}{\langle n \rangle^2} = \frac{\Omega_B^2}{\langle \Delta E \rangle^2} = \frac{\langle T \rangle}{\langle \Delta E \rangle} = \frac{1}{\kappa}, \tag{2}$$

where $\langle \Delta E \rangle$ is average energy deposition, Ω_B^2 is the energy deposition variance, $\langle T \rangle$ is an average energy transfer per an electron-ion interaction (see Appendix B), κ is an average number of the electron-ion interaction in the sensitive region.

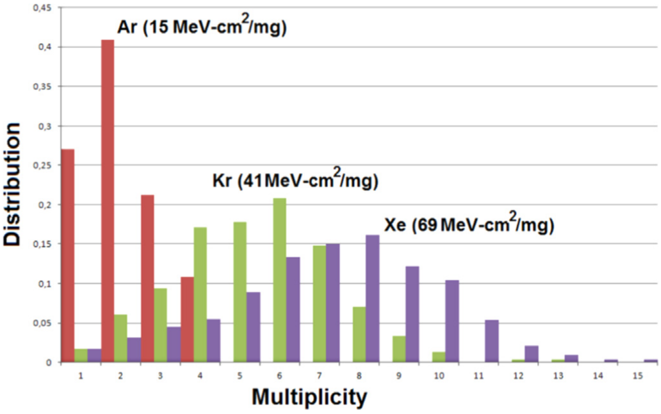

Fig. 1. Multiplicity distributions for IC with technology node 90 nm for different LETs [13]. All ions correspond approximately to the same specific energy ~3.5 MeV per a nucleon.

Fig. 1 shows detailed statistical information about multiplicity distributions, obtained by comparing physical and logical upset addresses in the 90 nm node memory, taken from [13].

The multiplicity distributions for the ions with different LETs are characterized by the two remarkable features. First, the average MCU multiplicity and average cross-section turned out to be approximately proportional to the ion LET. Second, the variance of the multiplicity distributions is also proportional to the variance of energy deposition and, correspondingly, to the ion LET (see Appendix D).

Fig. 2 shows the experimental multiplicity distributions for different ions combined with the analytic distributions of energy-loss straggling (see Appendix B and C). The values of the critical energy and charge, effective charge collection length were determined by a fitting procedure. Interestingly, the extracted value of the critical charge corresponds almost exactly to an estimation with an old empirical formula [16] $Q_C \cong 23\,(L_{node}/\mu m)^2$ fC~0.16 fC for L_{node}=90 nm.

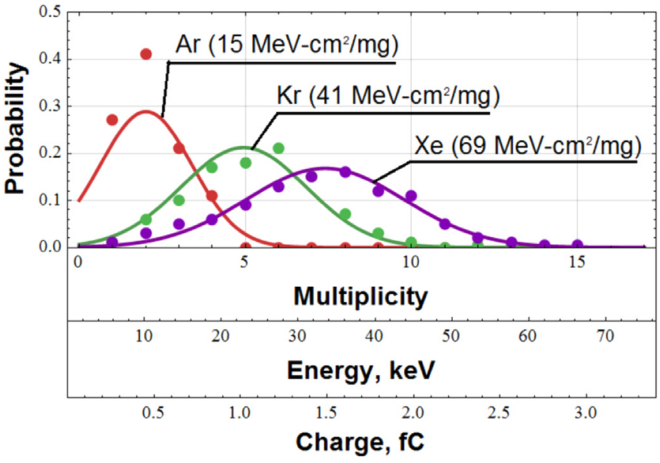

Fig. 2. Calculated (lines) and experimental (points [13]) multiplicity distributions for IC with technology node 90 nm for different LETs, the nominal layout cell area a_{cell}=0.8 μm². Extracted parameter t_{eff}=2.6 nm, ε_C=4.5 keV, Q_C=0.2 fC. η(Ar)=1, η(Kr)=0.9, η(Xe)=0.8 (see Appendix B and C).