Impact of recombination on heavy ion induced single event upset cross-section

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Abstract. The experimental dependence of the single event upset (SEU) cross-section versus linear energy transfer (LET) function in the nanoscale (with feature size less than 100 nm) memories is explained with the proposed recombination-limited charge yield, which is significantly dependent on LET.

1. Introduction
Modern high-scaled integrated circuits have a very high sensitivity to single event effects (SEE) due to their low critical charges and small sizes of microelectronic components [1]. The feature size of cells on digital memory circuits becomes smaller than heavy ion tracks, which leads to multiple cell upsets (MCUs), when a single particle can cause more than one simultaneous errors [2]. Low critical charges of memory cells are a consequence of supply voltage lowering in high-scaled memories. As a result, the noise margin of integrated circuits reduces and circuits become more susceptible to ionizing radiation.

If deposited charge of the heavy ion is greater than a critical charge of the memory cell, it may lead to SEU. It is supposed that deposit charge is proportional to deposit energy from heavy ion, but it is right only for a moment of interaction. In fact, effective charge yield reduces because of recombination. For many cases of ionizing radiation, reducing of charge yield can be neglect because of the low density of electron-hole pairs, but heavy ion’s hit make the high density of electron-hole pairs in slim ion’s track. In this case reducing of charge yield because of recombination is significant.

We in this paper derive an experimental form of the SEU cross-section versus LET function of nanoscale memory. The experimental form is explained by the recombination-limited charge yield dependence on LET.

2. Cross-section interpolation and electron–hole recombination at the high LET

2.1. Logarithmic approximation
The SEE sensitivity characterization methods include the interpolation of average cross-section dependence by means of the Weibull function [3]:

$$\sigma(A) = \sigma_{SAT} \left( 1 - \exp \left[ - \left( \frac{A - \Lambda_c}{W} \right)^\gamma \right] \right).$$  \hspace{1cm} (1)
The Weibull function has four parameters, where two of them (the saturation cross-section $\sigma_{\text{SAT}}$ and the threshold (critical) value of LET ($\Lambda_c$)) are main parameters and other two (determine the shape of the cross-section curve in a subthreshold region $W$ and the shape of a transition region between the subthreshold and the above-threshold parts of the curves $s$) are adjusting.

Recent studies show the absence of saturation in the cross-sections up to 120 MeV·cm$^2$/mg (see figure 1, taken from [4]). Therefore, a use of Weibull interpolation leads to problems related to an uncertainty of main parameter $\sigma_{\text{SAT}}$, which requires a distinct saturation of the curve, and extraction procedures.

![Figure 1](image_url)

Figure 1. Experimental data points of a cross-section in a wide range by LET [4].

A lack of saturation means, properly, that the Weibull parameter $\sigma_{\text{SAT}}$ is dependent on a range of LET, especially on the maximum experimental LET value. This dependence produces ambiguity of parameters extraction procedure.

The more precise way to describe average cross-section dependence is using cross-section versus LET curve logarithmic approximation, which proposed in [5]:

$$\sigma(\Lambda) = K_d W \ln \left[ 1 + \exp \left( \frac{\Lambda - \Lambda_c}{W} \right) \right], \quad (2)$$

where $K_d$ is the differential slope of quasi-linear part of the above-threshold cross-section versus LET curve, $W$ is an adjusting parameter for the subthreshold region.

2.2. Effective charge yield dependence at high LETs as recombination limited process

Equation (2) implies a quasi-linear shape of $\sigma(\Lambda)$ in the above-threshold region. This assumption appropriate for relatively narrow LET ranges used in measurements [6]. For wide LET ranges (up to 120 MeV·cm$^2$/mg) the dependence in the above-threshold region has sub-linear shape. This conclusion is made from detailed analysis of experimental data [4]. Such a sub-linear dependence may be explained by reducing the electron–hole charge yield for the high-LET ions due to increased recombination at high injection levels:

$$\sigma(\Lambda) = \eta_{\text{eff}}(\Lambda) K_d W \ln \left[ 1 + \exp \left( \frac{\Lambda - \Lambda_c}{W} \right) \right], \quad (3)$$
where \( \eta_{\text{eff}}(\Lambda) \) is an effective charge yield, which assumed to be a decreasing function of the injection level, dose rate and LET, because this parameter is limited by the recombination process of the charge carriers excess.

The initial bulk electron–hole concentration can be estimated as follows:

\[
\Delta p_0 = \Delta n_0 = \frac{\Lambda \rho}{\varepsilon_{\text{e-h}} S_{\text{track}}} \equiv K_A \Lambda,
\]

where \( \rho \) is the silicon mass density, \( S_{\text{track}} \) is an effective transversal area of the ion track, \( \varepsilon_{\text{e-h}} \) is an energy required for generation of an electron–hole pair (3.6 eV in silicon).

The effective ion-induced electron–hole concentration is the difference between the initial value \( \Delta n_0 \) and the value recombined during the charge collection time. An effective charge yield dependence on LET \( \eta_{\text{eff}}(\Lambda) \) can be obtained from this equation:

\[
\eta_{\text{eff}} \Delta n_0 = \Delta n_0 - \tau_c R,
\]

where \( \tau_c \) is the charge collection time, \( R \) is recombination rate, which contains bimolecular recombination \( R_B \) and Auger recombination \( R_A \):

\[
R = R_A + R_B.
\]

The Auger recombination rate can be estimated as follows:

\[
R_A = c_{nA} n^2 + c_{pA} np^2,
\]

where \( c_{nA} \equiv 2.28 \times 10^{-31} \text{ cm}^{-6} \cdot \text{s}^{-1} \) and \( c_{pA} \equiv 9.9 \times 10^{-32} \text{ cm}^{-6} \cdot \text{s}^{-1} \) are Auger recombination constants [7]. We use it here in a simplified form:

\[
R_A = 2C_A \Delta n_{0A},
\]

where \( C_A = 1.6 \times 10^{-31} \text{ cm}^{-6} \cdot \text{s}^{-1} \), \( n = p = \Delta n_{0A}(\Lambda) = \eta_{\text{eff}} \Delta n_0(\Lambda) \). The bimolecular recombination rate can be estimated as follows:

\[
R_B = C_B np = C_B \Delta n_{0B}^2,
\]

where \( C_B \approx 10^{-12} \text{ cm}^{-4} \cdot \text{s}^{-1} \) is coefficient of bimolecular recombination. From (5) - (9) we can get self-consistent non-linear equation for effective charge yield:

\[
\eta_{\text{eff}} = 1 - f_A \eta_{\text{eff}} - f_B \eta_{\text{eff}}^2,
\]

where functions \( f_A \) and \( f_B \) are defined as follows:

\[
f_A(\Lambda) = 2\tau_c C_A \Delta n_0^2 = 2\tau_c C_A K_A^2 \Lambda^2 \equiv \left( \frac{\Lambda}{\Lambda_A} \right)^2, \\
f_B(\Lambda) = \tau_c C_B \Delta n_0 = \tau_c C_B K_B \Lambda \equiv \frac{\Lambda}{\Lambda_B}.
\]

Equation (10) has the exact solution:

\[
\eta_{\text{eff}} = \frac{1}{6f_A} \left( \frac{2^{1/3} \left( 27 f_A^2 + 9f_A f_B - 2f_B^3 + 3\sqrt{3} \left( f_A^2 \left( 27 f_A^2 - f_B^2 (1 + 4f_B) + 2f_A (2 + 9f_B) \right) \right) \right)^{1/3}}{\left( 27 f_A^2 + 9f_A f_B - 2f_B^3 + 3\sqrt{3} \left( f_A^2 \left( 27 f_A^2 - f_B^2 (1 + 4f_B) + 2f_A (2 + 9f_B) \right) \right) \right)^{1/3}} \right)^{1/3} - 2f_B \left( 3f_A - f_B^3 \right) \left( 27 f_A^2 + 9f_A f_B - 2f_B^3 + 3\sqrt{3} \left( f_A^2 \left( 27 f_A^2 - f_B^2 (1 + 4f_B) + 2f_A (2 + 9f_B) \right) \right) \right)^{1/3}
\]

(13)
Results of modeling equation (3) with calculated charge yield from (13) are shown in figure 2.

**Figure 2.** Cross-section vs LET for IC with SOI technology node 45-65 nm [4] interpolated with equation (3) at $K_d = 1.4 \times 10^{-2} \text{mum}^2/(\text{MeV-cm}^2/\text{mg})$, $W=0.35 \text{MeV-cm}^2/\text{mg}$, $\Lambda_C = 1.2 \text{MeV-cm}^2/\text{mg}$, $\tau_C = 1 \text{ns}$, $S_{\text{track}} = 8.5 \times 10^{-11} \text{cm}^2$.

3. Conclusion

We have presented a new approach for charge carriers recombination’s influence on cross-section versus LET curve. This approach improves traditional SEE sensitivity characterization methods by accurately describing effective charge yield dependence at high LETs as limited recombination process. The sub-linear SEU cross-section dependence as a function of the ion LET is explained by reducing the electron–hole charge yield for the high-LET ions due to increased recombination. Increasing recombination at high injection levels is considered as Auger and bimolecular recombination processes in this approach. Using this new proposed way, modeling results show distinct accordance with experimental data, which provide evidence of improved precision.

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