CORRELATION OF ION- AND PROTON-INDUCED SINGLE EVENT UPSETS

A.I.Chumakov
Specialized Electronic Systems
31 Kashirskoe shosse, Moscow, 115409 Russia, AICHUM@SPELS.MSK.RU

Abstract

Two-parameters model of ion-induced single event upsets is suggested. Saturation cross section of single event upsets and threshold linear energy transfer are required to estimate the cross section as a function of linear energy transfer. Comparison of this two-parameter dependence with Weibull function for various integrated circuits is done. Correlation of these two parameters with two parameters of Bendel approximation or of computer model for proton-induced single event upsets is discussed.

1. INTRODUCTION

Single event upsets (SEUs) are the main reason for functional errors of VLSI in low intensity radiation of nuclear particles [1-3]. The single event upset is a bit flip in a digital element that has been caused either by the direct ionisation from a traversing particle or by the ionisation produced by charged particles and recoiling nuclei emitted from a nuclear reaction induced near the microcircuit element.

The SEU rate prediction needs experimental SEU cross section dependencies on energy for proton irradiation and on linear energy transfer (LET) for ion irradiation. These dependencies are obtained from proton and ion accelerator tests for various energies or LETs. Such approach is rather complex and expensive and it would like to obtain a relation between sensitivity parameters of proton- and ion-induced SEUs. It is possible because of a common nature of proton or ion-induced SEUs. The common reason is a generation of a critical local charge in a sensitive volume of IC elements. The main issue of this work is the determination of correlation between proton- and ion-induced upset cross section dependencies.

2. PROTON-INDUCED SEU CROSS SECTION

The proton-induced SEU prediction methods are based on SEU cross section dependence on a proton energy. Two different approaches to proton-upset cross section calculations are developed now [4]. The first one is concerned with a nuclear reaction analysis in a microvolume of IC elements [5]. The semiemperical approach based on Bendel model is used as the second one [6]. The each model needs only two parameters. As a rule, a prediction of SEU cross section dependence on proton energy needs a threshold energy (E_o) and a sensitive volume value (V_{sp}) in digital models. Bendel approximation is based on the following expression:

$$\sigma_p = \sigma_{ps} \cdot [1 - \exp(-0.18 \cdot \sqrt{\sqrt{(18/A_p)}(E_p - A_p)})]^4; \quad (1)$$

where E_p is a proton energy; A_p, σ_{ps} are approximation coefficients; σ_{ps} is a proton-induced SEU saturation cross section; A_p is a threshold parameter.

Therefore there are only two independent parameters in both methods. It is clear that there is a connection between them. Let's determine the threshold proton energy (E_{po}) from the condition $\sigma_p = 0.05\sigma_{ps}$. Then one can write:

$$E_{po} = 19.775\ (A_p/10)^{0.7885}; \quad (2)$$

It is necessary to point out that the real value of E_{po} must be more than a threshold energy of proton-induced nuclear reaction in Si ($\approx$ 15 MeV). The value of E_{po} estimated from equation (2) may be less than 15 MeV due to formal fitting of Bendel function to the experimental results.

Taking into account the simplest model of proton-induced nuclear reaction in Si the relation between E_{po} and E_o can be written as:

$$E_o = E_{po}/k_{po} - \Delta Q; \quad (3)$$

where k_{sp}, ΔQ are approximation coefficients (satisfactory correspondence are obtained for k_{po} =2.9 and ΔQ = 0.69 MeV).

The connection between σ_{ps} and V_{sp} can be obtained from the following equation [7]:

$$\sigma_{ps} = V_{sp}\ \Sigma_{ns}\, f(> E_o); \quad (4)$$

where Σ_{ns} is a macroscopic cross section of proton-induced nuclear reaction in Si; $f((\Delta E > E_o)$ is a probability of energy losses more than E_o in a sensitive volume from secondary nuclei;

$$V_{sp} \cong \sigma_{is}\ d_{sp}; \quad (5)$$

σ_{is} is an ion-induced SEU saturation cross section; d_{sp} is a thickness of a sensitive volume. The equation (4) can be solved digital methods [7]. The approximate decision of the equation (4) can be written as:

$$\sigma_{ps} = k_{sp}\ V_{sp}^{(1+Eo/E1)} \exp(-E_o/E_2); \quad (6)$$

where k_{sp}, E_1 and E_2 are approximation coefficients. A satisfactory agreement of approximation curves with

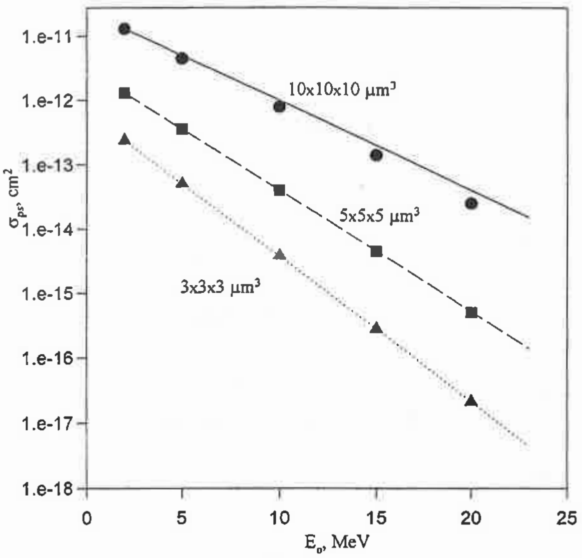

Fig.1. Proton-induced saturation cross section as a function a threshold energy for different values of sensitive volume of IC element. Curves - approximation (5); symbols - computer model [5].

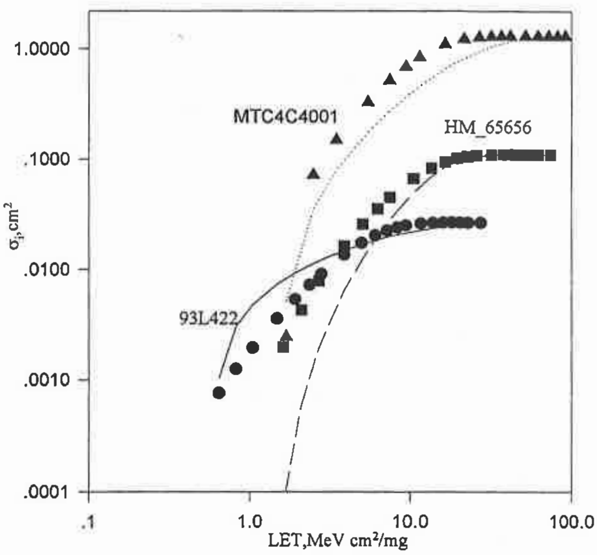

Fig.2. Ion-induced cross section Vs. LET for MT4C4001, HM_65656 and 93L422. Symbols - standard Weibull functions; curves - simplified two-parameters Weibull functions

digital calculation curves [5,7] was obtained for k_{sp} =2.5 10^{-14} cm^2; E_1 = 18.3 MeV and E_2 = 1.43 MeV (Fig.1).

One can use the only typical value of the sensitive thickness ($d_{sp} \approx 1.5$ μm) because of the mutual correlation between σ_{ps}, E_o and d_{sp} [7]. Therefore the physical parameters (E_o and V_{sp}) of proton-induced SEU cross section dependencies on proton energy can be calculated using Bendel approximation parameters (A_p and σ_{ps}) and vice versa. Moreover the correlation of these parameters with ion-induced saturation cross-section is obtained also.

3. ION-INDUCED SEU CROSS SECTION

The ion-induced SEU prediction methods are based on the SEU cross section dependence on LET. Typically, the cross section curve for ion-induced SEU can be fit by the Weibull function with four parameters:

$$\sigma_i(LET) = \sigma_{is}\cdot\{1 - \exp[-((LET-LET_o)/W)^s]\}; \quad \text{for } LET > LET_o; \qquad (7)$$

where LET_o is a threshold LET; W and s are approximation coefficients. It is preferable to decrease the number of parameters in the function (7). The satisfactory results are obtained for two independent IC's SEU sensitive parameters (LET_o and σ_{is}) and supposing that s=1.5 and W depends on LET_o and on a peripheral area of sensitive volume of IC elements. The possible approximation for W(LET_o, σ_{is}) looks as:

$$W = k_w \cdot LET_o^{\chi} \cdot [1+k_p \cdot \sigma_{is1}^{\beta}]; \qquad (8)$$

where σ_{is1} is an ion-induced SEU saturation cross section per one bit; k_w, χ, k_p and β are approximation coefficients.

Only the ion-induced cross section and threshold LET_o are used in this case. The simplified Weibull functions for some IC are shown in Fig.2. Satisfactory agreement between the two-parameter function and usual Weibull curves [2, 8] is obtained. Therefore two-parameter curves can be used for determination of ion-induced SEU cross section dependence on LET.

It is important to point out that LET_o is connected with E_o:

$$LET_o = E_o/d_{si}; \qquad (9)$$

where d_{si} is an effective thickness of the IC sensitive volume [9]. Taking into account the funnelling effects one can consider that $d_{si} = (2\text{-}4)\cdot d_{sp}$.

4. CORRELATION PROTON-AND ION-INDUCED SEU PARAMETERS

It is possible to use heavy ion data for estimating the energy dependence of the proton-induced SEU cross section and vice versa. Really one can assume that a sensitive volume of an IC element is a right rectangular parallelepiped and its area is proportional to SEU ion-induced saturation cross-section per bit. The threshold LET equals to threshold energy divided by an effective thickness of the parallelepiped (9). In addition to one can use the relation (6) between SEU threshold energy and proton-induced saturation cross section.

Proton-induced SEU parameters can be determined both for Bendel function and for digital model. Technique for estimation parameters of digital model consists of the following steps:

- determination of σ_{is} and LET_o from experimental results;

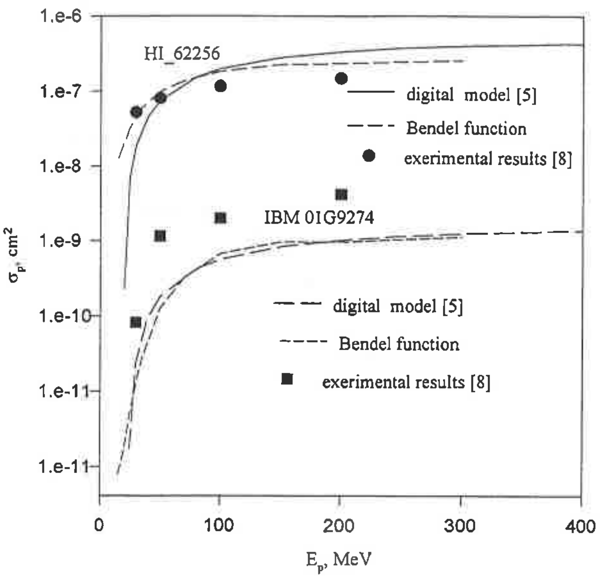

Fig.3. Proton-induced SEU cross sections as a function of a proton energy estimated using ion-induced SEU sensitivity parameters

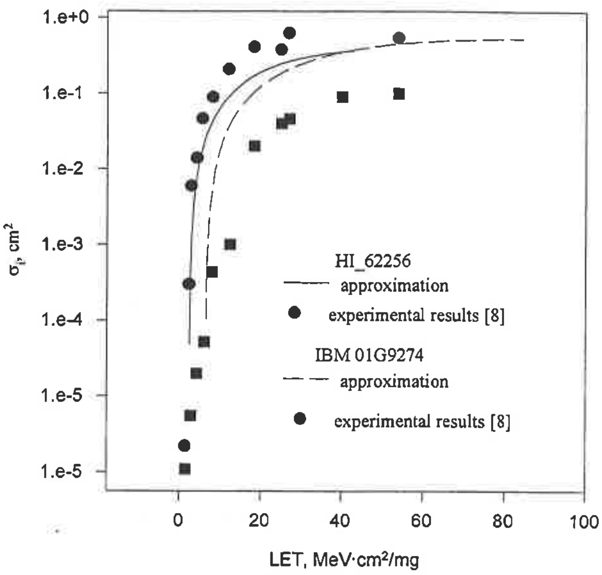

Fig.4. Ion-induced SEU cross sections as a function of a LETestimated using proton-induced SEU sensitivity parameters

- estimation of E_o from (7) (the best correspondence is obtained if $E_o=(LET_o+LET_{01})\cdot d_{si}/2$; where LET_{01} is defined as the threshold at 0.1 of σ_{is};
- determination of V_{sp} from (5);
- calculation of $\sigma_p(E_p)$.

The proton-induced SEU cross section dependencies on proton energy can be calculated using computer code [5] and parameters (E_o and V_{sp}) estimated with help of this technique. The final curves of $\sigma_p(E_p)$ and experimental data [8] are shown in Fig.3 for HI_62256 and IBM 01G9274.

The similar technique can be used for estimation of Bendel function parameters. In fact one can estimate A_p with help of the following equation [4]:

$$A_p = LET_{01} + 15; \qquad (10)$$

and σ_{ps} using equation (6). Bendel curves are shown in Fig.3 also. One can see that the both models give a satisfactory correspondence with experimental results.

The similar approach can be applied to estimation of ion-induced SEU cross section dependence on LET based on proton results. Technique for estimation parameters of the simplified Weibull function model consists of the following steps:

- determination of E_{po} and σ_{ps} from experimental results;
- estimation of E_o and V_{sp} from the best correspondence of calculating curves to experimental results [5] or from a decision of equations (3) - (5);
- calculation of σ_{is} and LET_o from equations (5), (6) and (9);
- estimation of W from equation (8);
- calculation of σ_i(LET) using function (7) with s=1.5.

This technique was applied to an estimation of ion-induced SEU cross section dependencies of HI_62256 and IBM 01G9274. The ion-induced cross section curves and experimental data [8] are shown in Fig.4. One can see a good correlation with LET_o but a significant difference for σ_{is}. In spite of the fact the proposed technique gives a chance to estimate the ion-induced and proton-induced SEU cross section dependencies using minimal set of independent experimental results.

Therefore, this approach requires two independent experimental results. Probably the better results would be obtained if the saturation cross sections of ion-induced SEUs and of proton-induced SEUs are used as independent parameters.

5. CONCLUSION

Simplified two-parameters models of ion-induced and proton-induced single event upsets were considered. The appropriate equations connecting the parameters of these models were suggested. Correlation of the parameters of ion- and proton-induced SEU models was discussed. Examples of a conversion of ion-induced SEU model parameters into proton-induced ones were performed. Comparison of the experimental data was done.

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