Assessment of the direct ionization contribution to the proton SEU rate

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***Abstract*—Proton direct ionization SEU sensitivity is related to the high integration scale of modern technologies. The sensitivity of electronic devices to low energy protons has previously been observed and many experimental data have been published. The purpose of this study is to use those data to assess a calculation method for determining the proton direct ionization contribution to the SEU rate. Different SEU rates are presented and the impact of calculation parameters on these rates is discussed.**

***Index Terms*—Low energy proton, direct ionization, SEU rate calculation, sub-90nm technologies.**

I. INTRODUCTION

Low energy protons may have a significant effect on highly integrated electronic devices. These types of components have experimentally presented an enhanced sensitivity to single event upsets induced by proton direct ionization. This phenomenon may occur when protons stop inside the active region of the component. In this case, the proton Bragg peak may be located in the sensitive area. As a result, the collected charge can exceed the critical charge necessary to generate a SEU. This phenomenon is likely to be observed with protons having an energy range from 0.5 to 1.5 MeV at die surface.

Many works have been carried out on the experimental characterization of highly integrated components about proton direct ionization. Low energy proton test data are already available in the literature [1]-[5]. Moreover, a calculation method for proton direct ionization induced SEU rate has already been proposed in a previous publication [6]. The purpose of this study is to apply this methodology to a large panel of already existing proton data.

The direct and indirect ionization proton rates will be compared and the impact of several calculation parameters – such as the altitude and the shielding – will be investigated. The work presented here has been achieved by TRAD with the support of the CNES (Centre National d'Etudes Spatiales).

II. BACKGROUND

The first part of this study consists in the selection of direct ionization experimental data from previous publications. The idea is to take benefit from previous studies that were done on the subject, as many low energy proton tests have been performed since the phenomenon of direct ionization was identified. A lot of experimental data are available in the literature. The selection was made in order to deal with different levels of integration. Low energy proton irradiations were principally conducted on SRAM memories. TABLE I presents the choices that were done for this study.

TABLE I
SELECTED TEST DATA

Paper	Component	Proton energy
D. F. Heidel, 2008 [1]	65 nm SOI SRAM	1 to 500 MeV
E. H. Cannon, 2010 [2]	90 nm SRAM	1 to 100 MeV
N. A. Dodds, 2015 [3]	20-90 nm technology nodes	1 to 60 MeV
D. F. Heidel, 2009 [4]	45 et 65 nm SOI SRAM	1 to 500 MeV
J. Wert, 2012 [5]	90 nm SRAM	1 to 2 MeV

In this abstract, only the example of a 55 nm bulk SRAM [3] will be developed. The corresponding proton test data are shown in Fig.1. The other cases will be presented in the final publication.

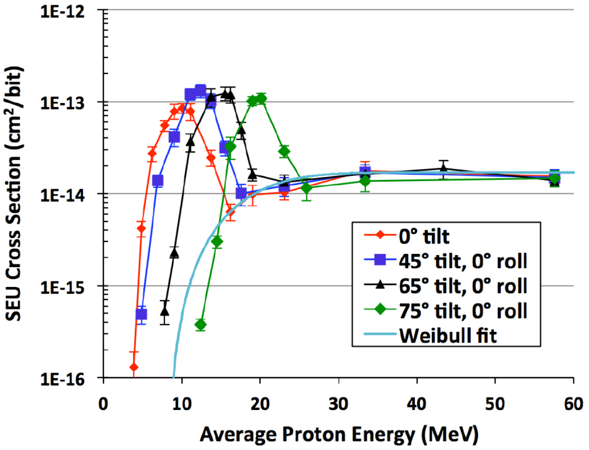

Fig. 1. Measured SEU cross sections for a 55 nm bulk SRAM [3]. The low energy proton cross section peaks show a dependence on the tilt angle.

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III. Proton Direct Ionization Rate Calculation

A. *Calculation methodology*

The calculation methodology used for the SEU rates provided in this study is presented in [6]. The calculation is based on low energy proton experimental data, measured – or recompiled – as a function of the incident tilt angle. A sensitive layer is determined in the device active region thanks to the experimental data, and the effective flux φ(θ) of protons ending their path in this sensitive layer is calculated at each angle. The measured cross section at low energy is then used to represent the device sensitivity. A step function at the low energy cross section peak σ_{peak} is considered here.

The SEU rate τ is calculated by multiplying the number of proton stopping in the sensitive layer by the low energy cross section peak (1).

$$\tau = \sigma_{peak} \int_{\theta} \varphi(\theta) d\theta \tag{1}$$

Only the cross section peak is considered here. In fact, the measured cross section σ(θ) shape at low energy can be very narrow, and its accuracy depends on the energy steps. This approach is a worst-case consideration.

Both phenomena of direct and indirect ionization are measured in the proton cross section. The separation of each effect is a critical point as there might be an overlapping between both regimes as shown on Fig. 2 [6].

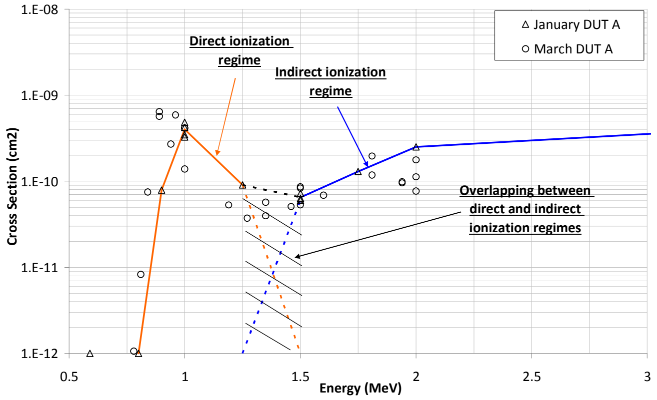

Fig. 2. Proton direct and indirect ionization regime overlapping schematic representation [6].

Indeed, a hypothesis is made for the threshold level extrapolation. This methodology has been implemented in a beta-version of OMERE 5.0 [7].

B. *OMERE 5.0 direct ionization module*

In order to consolidate the proposed methodology for proton direct ionization SEU calculation, a specific module has been developed in OMERE 5.0. Indeed, it is more convenient to set up a routine for automatic calculation of relations between angles and energy for test data. The energy threshold is also determined. The software is able to provide the graphs for the low energy proton cross section as a function of the energy or tilt angle.

IV. Data Treatment

The data previously presented has been used for the SEU rate calculations. Cross section curves are available as a function of the energy but also at different angles for a fixed energy. The software is able to compile several pieces of cross section curves obtained at different angles and energies into one single curve (Fig. 3 and Fig. 4). The cross section curve as a function of the tilt angle is plotted for a fixed equivalent energy – 18 MeV in the case of Fig. 4. This energy value is a user parameter. It should correspond to the maximum energy at which direct ionization effects are preponderant.

V. Direct Ionization Contribution To The Trapped Proton SEU Rate

In a first step, it is interesting to look at the SEU rate for an usual orbit, with an external proton-induced stress. As a consequence, the rates for proton direct ionization were calculated using AP8 min for a LEO 800 km orbit. The calculations were done considering an aluminum shielding of 1g/cm². This direct ionization SEU rate is then compared to the indirect ionization rate. In order to take into account high energy protons, a Weibull fit is applied on the high energy data (Fig. 1).

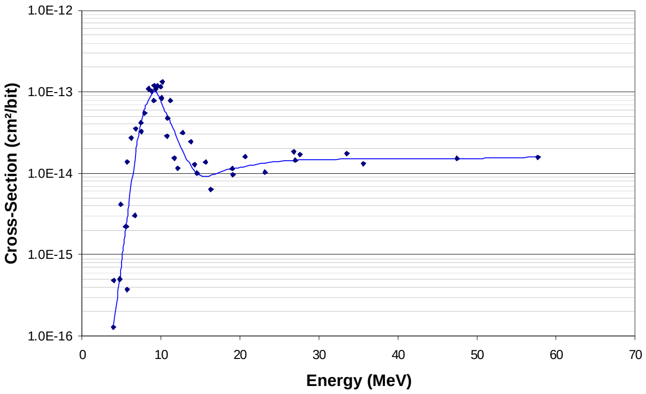

Fig. 3. Computed proton cross section curves, using the data of Fig. 1. as a function of the energy.

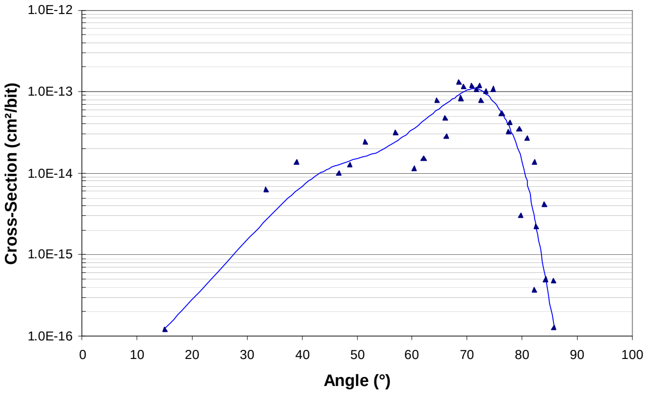

Fig. 4. Computed proton cross section curves, using the data of Fig. 1 as a function of the tilt angle at 18 MeV.

The corresponding Weibull parameters are indicated in TABLE II [3].

TABLE II
WEIBULL PARAMETERS

E_{th}	σ_{sat}	W	S
8 MeV.cm²/mg	1.7E-14 cm²/bit	12	2

The calculated SEU rates are presented in TABLE III. The direct ionization rate is higher than the indirect one. However, both rates remain within the same order of magnitude.

TABLE III
CALCULATED SEU RATES – AP8 MIN LEO 800 KM

Data	Direct ionization SEU rate	Indirect ionization SEU rate	Ratio
55 nm bulk SRAM [3]	2.02E-07 /bit/day	1.31E-07 /bit/day	1.54

Other examples will be presented in the final publication. The Weibull fit parameters for the indirect ionization rate calculation are not always available or computable. In these cases, a Weibull step function has therefore been used in order to keep a worst-case approach.

VI. IMPACT OF THE CALCULATION PARAMETERS

A. Environmental parameters

The impact of the environment has been investigated. Indeed, as low energy protons are the particles responsible for direct ionization, the orbit is a key parameter for the occurrence of direct ionization induced SEU. Considering the AP8 min model, the worst-case altitude location has been investigated using OMERE software [7]. It was determined that an altitude around 4000 km presents the highest fluxes of low energy protons through an aluminum shielding of 1 g/cm². This does not correspond to the proton belt center, but to the altitude where the protons flux with the adequate energy – to cross the shielding and have a remaining energy between 0.5 and 1.5 MeV – is maximum. The proton direct ionization SEU rate at 4000 km is indicated in TABLE IV.

TABLE IV
SEU RATES WITH 1G/CM² OF ALUMINIUM SHIELDING
FOR 55 NM BULK SRAM [3]

Altitude	Direct ionization SEU rate	Indirect ionization SEU rate	Ratio
800 km	2.02E-07 /bit/day	1.31E-07 /bit/day	1.54
4000 km	2.26E-05 /bit/day	5.32E-06 /bit/day	4.25

Trapped protons, AP8 min LEO 800 km and 4000 km, 1 g/cm² Al

The rates ratio is also indicated in TABLE IV to put in evidence that the altitude has an impact on the direct ionization contribution to total SEU rate.

B. Incident proton flux transportation

The importance of the shielding has also been investigated as this parameter impacts the transmitted low energy proton flux inside the spacecraft. SEU rate were calculated with and without shielding are presented in TABLE V. The results show that the shielding highly mitigates low energy proton fluxes.

TABLE V
SEU RATES WITHOUT ALUMINIUM SHIELDING
FOR 55 NM BULK SRAM [3]

Altitude	Direct ionization SEU rate	Indirect ionization SEU rate	Ratio
800 km	1.05E-06 /bit/day	1.84E-07 /bit/day	5.71
4000 km	1.38E-03 /bit/day	2.24E-05 /bit/day	61.6

Trapped protons, AP8 min LEO 800 km and 4000 km, 0 g/cm² Al

C. User settings

Some user hypotheses are done within the methodology presented here. For example, the energy threshold levels may have an important impact on the final result, as well as the acceptance of the direct ionization cross section peak. The Weibull parameters for the high energy proton rate are also user-defined. These dependences will be discussed in the final publication.

VII. DISCUSSION

The calculations presented on a single example here were conducted on all the test data available in [1]-[5]. It was interesting to compare all the results between direct and indirect method in order to assess the methodology proposed here. It was done using the ratio between direct ionization rate and indirect ionization rate, as comparison criterion. All the ratios calculated are given in TABLE VI.

The computed SEU rates are consistent between each other as direct and indirect ionization usually have the same order of magnitude. However, even if the predominance of one phenomenon with respect to the other seems variable, all rates evolve in a relevant way when the altitude and the shielding are varied.

Finally, the low energy proton contribution in the case of the 55 nm bulk SRAM has been estimated here at 60% of the proton rate in LEO configuration, whereas it is about 20% in [3]. This gap can be attributed to three potential differences: the environment model selection, the low energy proton flux at sensitive volume level calculation and the sensitive volume definition. This observation will be discussed in the final publication.

VIII. CONCLUSION

Thanks to previous work about proton direct ionization reported in the literature, low energy proton test data were gathered. These data were used to calculate rates for the SEU induced by proton direct ionization, and to assess the calculation methodology previously proposed in [6]. The direct ionization module prototype developed in OMERE 5.0 has also been improved.

The results have been compared to observations and conclusions obtained in previous publications. The impact of different calculation parameters has been studied.

TABLE VI
Direct And Indirect Ionization SEU Rate Ratios

Source	Test	Technology	LEO 800 km		LEO 4000 km	
			0 g/cm^2	1 g/cm^2	0 g/cm^2	1 g/cm^2
[1]	SRAM data 0	65 nm	233.8	0.251	206.2	1.342
[1]	SRAM data 1	65 nm	233.8	0.253	207.2	1.354
[2]	SRAM Cell B 0.9V	90 nm	4.691	0.006	4.299	0.169
[2]	SRAM Cell B 1.0V	90 nm	2.029	0.003	1.858	0.014
[2]	SRAM Cell B 1.1V	90 nm	1.482	0.002	1.328	0.009
[2]	SRAM Cell C 0.9V	90 nm	0.258	0.047	3.596	0.169
[2]	SRAM Commercial Cell 0.9V	90 nm	1 963	2.724	1 838	14.39
[3]	Bulk flip-flop	20 nm	10.28	1.647	244.6	5.932
[3]	SRAM bulk	55 nm	5.71	1.54	61.6	4.25
[4]	SRAM 1.3V	45 nm	160.7	0.709	259.7	3.427
[4]	SRAM 1.2V	65 nm	522.1	0.962	572.6	4.916
[4]	SRAM 1.2V	65 nm	11.42	0.297	41.47	1.323
[5]	SRAM 0.9V	90 nm	179.4	0.227	165.7	1.205
[5]	SRAM 1.0V	90 nm	236.7	0.259	209.4	1.380
[5]	SRAM 1.1V	90 nm	79.41	0.100	73.18	0.530
[6]	FPGA SRAM	45 nm	0.682	0.003	0.966	0.017

Ratios are calculated dividing the direct ionization SEU rate by the indirect ionization SEU rate. Values above 1 indicate that direct ionization is the predominant mechanism.

This study also investigated the environment selection and the flux transportation impact on the SEU rates caused by proton direct ionization.

The impact on devices is variable as they may not be all sensitive to direct ionization in the same way. Some cases showed that the contribution of this effect can reach more than 70% of the total SEU rate. The importance of this contribution is also developed in [3].

The work presented in [3] postulates that a good approach to take into account low energy protons is to consider their contribution to the rate being 5 times higher than the calculated rate for other contributions. In the work presented here, only the trapped proton contribution has been assessed with respect to direct ionization. However, the ratios presented in TABLE VI are consistent with this conclusion. At 800 km of altitude behind 1g/cm^2, all ratios are below 5, and only two ratios at 4000 km behind are above. Considering the results of this study, this hypothesis is adequate for a LEO orbit 800km – with a shielding of 1g/cm^2. However, in this some particular cases a margin factor of 5 for the direct ionization may not be enough at the altitude of 4000 km, considered as worst-case for trapped protons.

Finally, the analysis presented here focused on the relative contribution of trapped protons. However, this work could be extended to average solar proton fluxes and solar flare fluences. The use of an isotropic solid sphere shielding is also a major potential improvement of this methodology as already mentioned in [6]. Moreover, reference [8] warns about the use of a solid sphere shielding as it generally overestimates the SEU rate due to direct ionization.

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