NUCL SCI TECH (2017) 28:13
DOI 10.1007/s41365-016-0153-z

Prediction of proton-induced SEE error rates for the VATA160 ASIC

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Received: 16 November 2015 / Revised: 8 March 2016 / Accepted: 10 March 2016 / Published online: 1 December 2016

Abstract We predict proton single event effect (SEE) error rates for the VATA160 ASIC chip on the Dark Matter Particle Explorer (DAMPE) to evaluate its radiation tolerance. Lacking proton test facilities, we built a Monte Carlo simulation tool named PRESTAGE to calculate the proton SEE cross-sections. PRESTAGE is based on the particle transport toolkit Geant4. It adopts a location-dependent strategy to derive the SEE sensitivity of the device from heavy-ion test data, which have been measured at the HI-13 tandem accelerator of the China Institute of Atomic Energy and the heavy-ion research facility in Lanzhou. The AP-8, SOLPRO, and August 1972 worst-case models are used to predict the average and peak proton fluxes on the DAMPE orbit. Calculation results show that the averaged proton SEE error rate for the VATA160 chip is approximately 2.17×10^{-5}/device/day. Worst-case error rates for the Van Allen belts and solar energetic particle events are 1–3 orders of magnitude higher than the averaged error rate.

This work was supported by the National Natural Science Foundation of China (Nos. 11179003, 10975164, 10805062, and 11005134).

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Keywords Proton · ASIC · Single event effects · Error rates

1 Introduction

VATA160 is a low-noise, low-power commercial application-specific integrated circuit (ASIC) chip designed by IDEAS (Norway). It is a core device in the electronics system of the sub-detectors on the scientific satellite Dark Matter Particle Explorer (DAMPE) [1–3]. The DAMPE satellite was launched at the end of 2015 for a mission period of at least 3 years. It is in a low Earth orbit (LEO) at an altitude of 500 km with an inclination angle of 97 degrees. During its service period, it will encounter energetic and high-flux protons from the space radiation environment such as solar energetic particle (SEP) events and the Van Allen belts, especially when passing through the South Atlantic Anomaly (SAA), an area of enhanced radiation at the lower edge of the Van Allen belts caused by the offset and tilt of the geomagnetic axis with respect to the Earth's rotation axis. These SAA protons could induce single event effects (SEEs) [4–7] in the semiconductor devices and prevent them from working correctly. VATA160 was fabricated using the standard 0.35 μm CMOS technology with an epitaxial layer and might therefore be susceptible to SEEs such as single event upsets (SEUs) and single event latch-ups (SELs). SEUs are negligible in our case. Even if they occur, they could be immediately eliminated by a reset or redundancy in the VATA160 chip. SELs, on the other hand, are a more serious concern for our electronic system designers because they are destructive effects and may lead to catastrophic failures. To guarantee the reliability of the readout electronics of the detectors, this paper evaluates the tolerance of the VATA160 chip to proton-induced SELs and calculates the corresponding error rates.

SEL error rates can be calculated by integrating the SEL cross-sections with the differential proton energy spectra in space, which are normally deduced from models such as the AP-8 radiation belt model [8, 9]. The SEL cross-section as a function of proton energy can be obtained by exposing the device to a known proton beam or calculated from heavy-ion (HI) tested results [8]. Due to our lack of available proton test facilities, we used a homemade Monte Carlo tool named PRESTAGE [10] to calculate the proton SEL cross-sections from the HI test data. HI tests of the VATA160 were performed at the HI-13 tandem accelerator of the China Institute of Atomic Energy (CIAE) in Beijing and with cyclotrons at the heavy-ion research facility in Lanzhou (HIRFL). These tested results are reported in Ref. [11]. The PRESTAGE calculation of the proton SEL cross-sections for the VATA160 chip is described in Sect. 2. In Sect. 3, the proton error rates under both average- and worst-case conditions are computed. The paper ends with the conclusion.

2 Proton cross-section calculations

Various methods that aim at deriving proton SEE sensitivity from HI test data have been proposed. Commonly used methods include semi-empirical models such as PROFIT [12–15], and Monte Carlo methods such as SIMPA [16, 17], PROPSET [7], and PRESTAGE [10]. The semi-empirical models are time saving, easy to use, and work well in some cases. But using them for SEL effect predictions could lead to inaccurate results [14, 18]. For instance, Edmonds [18] reported that using empirical methods to calculate the proton SEL cross-section for the HM65162 chip could lead to a calculation error of more than 200 times the cross-section. Monte Carlo methods, on the other hand, are capable of giving more accurate predictions [7, 10]. Previous work has shown that the calculation errors of PRESTAGE are within a factor of 2–3 when predicting proton SEL cross-sections [10]. In our work, we use PRESTAGE to calculate the proton SEL cross-sections of the VATA160.

PRESTAGE calculations for the VATA160 involved three processes: device modeling, effect simulation, and cross-section calculation. In the device modeling process, VATA160 was defined as a silicon box containing a rectangular parallelepiped (RPP) sensitive volume (SV) by adding 10 μm to the length, 10 μm to the width, and 5 μm to the bottom of the SV. Alia et al. [19] showed that tungsten that exists in some devices potentially has a strong impact on the SEL cross-sections. Because no such high-Z materials were contained in the VATA160, we simply added a 5-μm-thick layer of silicon oxide on top of the SV to represent the passivation layers. The critical charge Q_c and the geometrical parameters of the SV (lateral dimensions D_x, D_y and thickness T_{SV}) indicate the sensitivity of the device to SEL. These sensitive parameters were mainly derived from the Weibull parameters fit using the HI test data.

Table 1 lists the HI test results [11] of VATA160 and the ion parameters used in the tests mentioned in Sect. 1. Figure 1 shows the test results fit by the Weibull function [8] as given by Eq. (1):

$$\sigma = \sigma_{sat}\left(1 - \exp\left(-\left(\frac{L - L_0}{W}\right)^S\right)\right). \tag{1}$$

The fitted Weibull parameters, i.e., the threshold LET L_0, saturated cross-section σ_{sat}, width parameter W, and the shape parameter S, were 11.0 MeV cm^2/mg, 17.6 × 10^{-4} cm^2/device, 44.2, and 2.67, respectively. These parameters were used as input to the PRESTAGE tool. The lateral dimensions of the SV, D_x, and D_y were determined by [8] $D_x = D_y = \sqrt{\sigma_{sat}}$. In reality, the SV of a device is composed of many small cells [20]. Our work, however, defined the surface of SV as a single region because the chip was tested under a broad HI beam, and the fine structure of the SV was not available. We have evaluated the impact of this parameter. Results show that taking the SV surface as a single region leads to conservative predictions in our simulation.

T_{SV}, the thickness of SV, cannot be calculated from the Weibull parameters. It is normally obtained by experimental methods such as destructive physical analysis, pulse laser tests, or HI experiments [21]. For the T_{SV} in this work, we used the value of 3 μm, taken from the laser study that revealed the SEL depth in technologies similar to the VATA160 [22].

Q_c, the minimum amount of charge that must be collected in the SV for the effect to occur, was calculated in units of fC using Eq. (2):

$$Q_C = 10.36 \times L_c \times T_{SV} \tag{2}$$

where T_{SV} is the thickness of the SV in units of μm, and L_c is the critical LET in units of MeV cm^2/mg. According to the studies of Petersen et al. [6, 7, 23], within the SV, different areas have different charge collection efficiencies and thus different SEE sensitivities. Following this location-dependent sensitivity strategy, we divided the SV of VATA160 into several sub-volumes V_1, V_2, …, V_i, …, V_N. These sub-volumes had an identical thickness (T_{SV}) but increasing top surface areas. For sub-volume V_i, L_c was derived by [7] using Eq. (3):

Table 1 Parameters of ions used in the VATA160 SEL tests and the test results [11]

Facility	Ion type	LET (MeV · cm^2/mg)	Φ (ions/cm^2)	N	σ (cm^2/device)
HI-13	^{27}Al	8.4	3.00×10^7	0	/
HI-13	^{35}Cl	13.1	2.75×10^7	16	5.82×10^{-7}
HI-13	^{35}Cl	15.0	1.00×10^7	24	2.40×10^{-6}
HI-13	^{48}Ti	21.8	9.22×10^6	160	1.74×10^{-5}
HIRFL	^{129}Xe	50.9	2.01×10^5	82	4.08×10^{-4}
HIRFL	^{129}Xe	64.5	1.67×10^5	103	6.17×10^{-4}

The ground test facility, the species, LET, fluence of the used ions, the number of tested SEL, and the SEL cross-section for the VATA160 chip

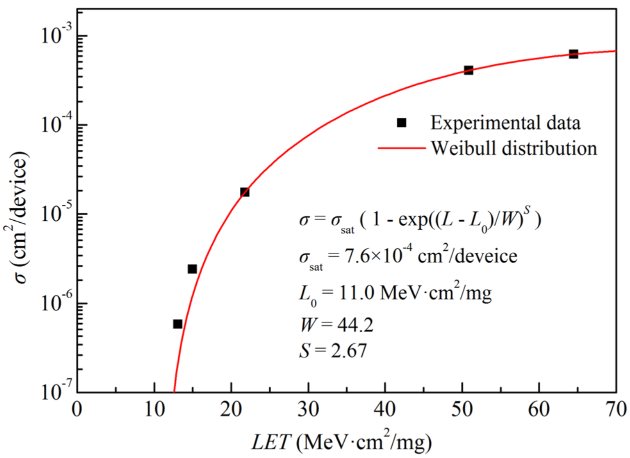

Fig. 1 HI-tested SEL cross-section σ varying as a function of LET for the VATA160 chip [11]. Weibull fitting of the test data is also shown

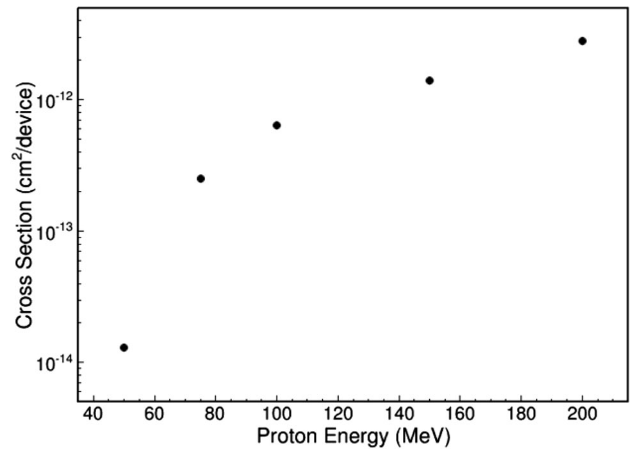

Fig. 2 PRESTAGE-calculated proton SEL cross-section as a function of proton energy for the VATA160 chip

$$L_c = L_0 + W\left[-\ln\left(1 - \frac{A_i}{A}\right)\right]^{1/S} \tag{3}$$

where L_0, W, A, and S are the Weibull parameters fit using the HI test data (see Fig. 1), and A_i is the top surface area of V_i in the SV.

During the simulation process of the effect, N_t protons were injected normally at the up surface of the device. After one proton penetration, an SEL was triggered if the generated charge exceeded the corresponding Q_c in more than one sub-volume. Then, the SEL cross-section was calculated using Eq. (4):

$$\sigma_p = \frac{N_e}{N_t} \times A_b \tag{4}$$

where σ_p is the calculated SEL cross-section induced by the proton; N_e is the total number of the SEL counted in the simulation, and A_b is the upper surface area of the device. Figure 2 shows the calculated SEL cross-section as a function of proton energy for the VATA160. The saturation cross-section induced by 200 MeV protons was 2.8×10^{-12} cm^2/device.

3 Calculation of the proton error rates in space

The particle radiations that we consider hazardous to the VATA160 are mainly protons from the Van Allen belts and SEP events. The proton SEE error rate can be determined by [8] Eq. (5):

$$R = \int \frac{d\Phi}{dE}(E) \times \sigma_p(E)dE. \tag{5}$$

In our case, R is the SEL error rate for the VATA160, $d\Phi/dE$ is the differential proton flux spectrum on the DEMPE orbit, and σ_p (E) are the PRESTAGE calculated proton cross-sections shown in Fig. 2.

In calculating the proton flux spectra, we used 100 mils of aluminum as the spacecraft shielding, following the recommendation of Ref. [8]. The AP-8-MIN [9] and Jensen-Cain 1960 geomagnetic field models were used to calculate the fluence and the peak fluxes of the trapped protons in the Van Allen belts during the mission. For calculations of the average and peak proton fluxes from SEPs, the SOLPRO and August 1972 worst-case models [24, 25] were used, respectively. The August 1972 SEP event is a widely used event for the worst-case analysis in the radiation effects community.

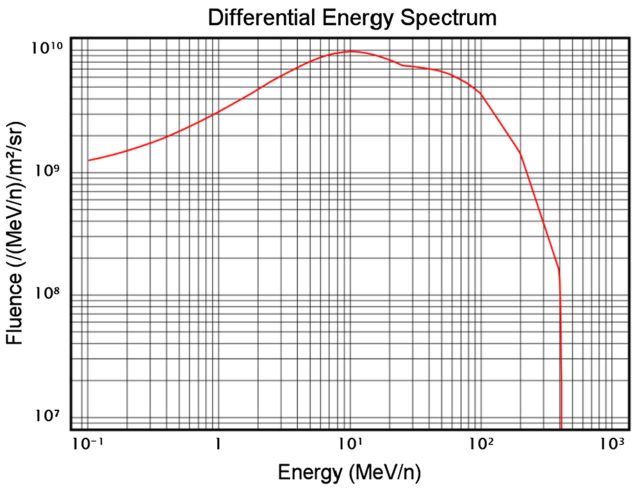

Fig. 3 Differential energy spectrum of the trapped protons in the Van Allen belts on the DAMPE orbit for a mission of 3 years

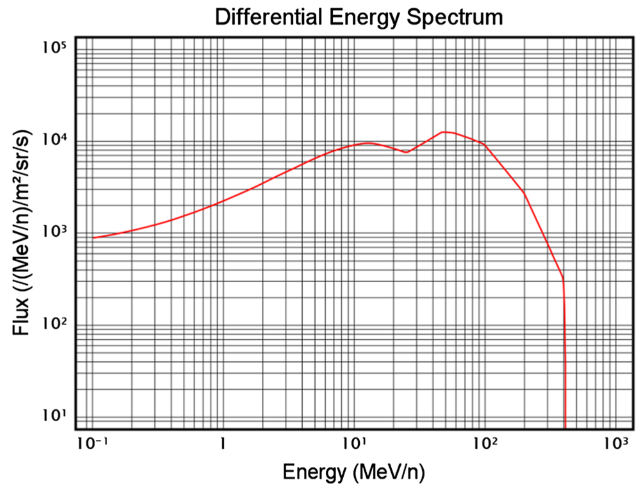

Fig. 4 Worst-case differential energy spectrum of the trapped proton on the DAMPE orbit

Figures 3 and 5 show the average proton differential energy spectra for the Van Allen belts and SEPs, respectively, on the orbit of DAMPE. Figure 6 shows the proton differential energy spectrum for the August 1972 SEP event. Figure 4 shows the peak differential energy spectrum for the trapped protons. The peak flux indicates the worst-case radiation environment for the trapped protons, and it was obtained by comparing the density of 10 MeV protons at each location on the orbit. This worst case occurred at 34.31 degrees south latitude and 34.60 degrees west longitude, near the center of the SAA. SEL rates of the VATA160 were calculated using Eq. (5) by integrating these fluences and fluxes with the SEL cross-sections shown in Fig. 2.

As shown in Table 2, which lists the calculated results for the VATA160 chip, the total averaged proton SEL error rate predicted by PRESTAGE is 2.178×10^{-5}/device/day. The worst-case error rates in the Van Allen belts and SPE radiation environments are 3.05×10^{-4} and 3.43×10^{-5}/device/day, respectively, which are much larger than the averaged ones. For comparison, calculation results using SIMPA [17] and PROFIT [15] are also shown. The SIMPA-calculated error rate is 9.8×10^{-6}/device/day, close to the calculation from PRESTAGE. The PROFIT-calculated result at 1.03×10^{-6}/device/day is about one order of magnitude less than the PRESTAGE and SIMPA calculations. Since 48 VATA160 chips are used in the satellite for a mission of at least 3 years, the number of expected SEL events on orbit is not negligible. Therefore, effective SEL protection circuits with a fast response should be added into the electronics system to avoid catastrophic damages.

The uncertainty in these error rates may come from several sources such as the radiation environmental uncertainty, shielding uncertainty, inaccuracy in the PRESTAGE predicted proton SEL and cross-sections. Despite the use of the Weibull fit to the HI test data, the determination of the SV size and shape and the critical charge might lead to some uncertainty in our PRESTAGE predictions. According to the comparison between the simulated and measured proton SEL cross-sections of several other devices, PRESTAGE is conservative and tends to give predictions that agree with the measured data within a factor of 2–3. The models that are used in the radiation environment specification could also lead to some uncertainties. For instance, the AP-8 model was used to describe the trapped proton radiation on DAMPE's orbit. This model was developed based on data from satellites flown in

Table 2 Calculated proton SEL error rates for the VATA160

Radiation specification		Flux/fluence used in the calculation	Calculated rate (/device/day)		
			PRESTAGE	SIMPA	PROFIT
Van Allen belts	Averaged	Accumulated fluence in Fig. 3	2.17×10^{-5}	9.80×10^{-6}	1.03×10^{-6}
	Worst-case	Peak flux in Fig. 4	3.05×10^{-4}	1.67×10^{-4}	2.58×10^{-5}
SEP	Averaged	Averaged flux in Fig. 5	7.74×10^{-8}	6.32×10^{-8}	1.89×10^{-8}
	Worst-case	Peak flux in Fig. 6	3.43×10^{-5}	4.83×10^{-5}	8.43×10^{-6}

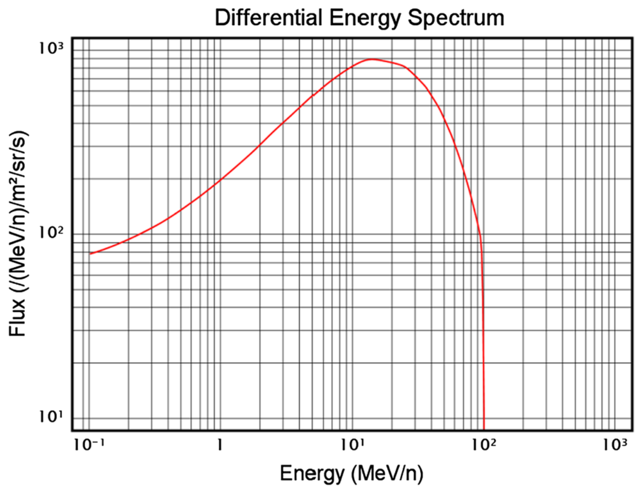

Fig. 5 Averaged differential energy spectrum for protons from SEPs on the DAMPE orbit

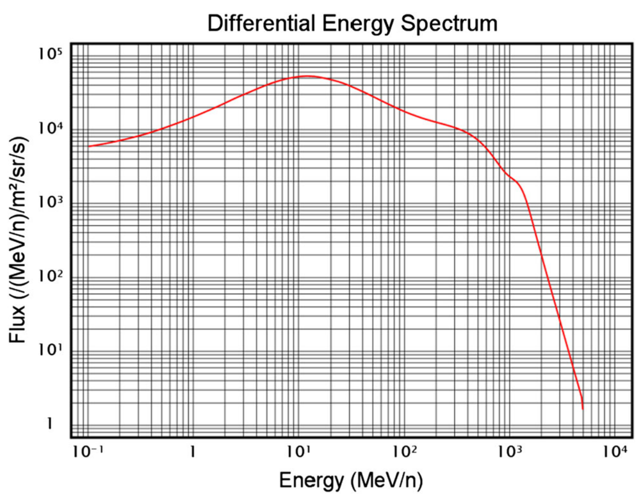

Fig. 6 Worst-case differential energy spectrum for protons from the August 1972 SEP event for the DAMPE orbit

the 1960s and early 1970s. Because the geomagnetic field is changing, the situation for DAMPE is no longer the same as when the model data were obtained. In addition, this model does not contain any flux directionality. According to the standard ECSS-E-ST-10-12C [8], the accuracy of the AP-8-predicted fluxes is within a factor of 2. These uncertainties should be carefully considered in the engineering margin design policy.

4 Conclusion

The averaged and worst-case proton SEL error rates for VATA160 on the DAMPE orbit were calculated by integrating the proton flux spectra and the proton SEL cross-sections as they varied with the proton energy. The Monte Carlo simulation tool PRESTAGE was used to simulate the proton cross-sections from the HI test data. The simulated saturation cross-section induced by 200 MeV protons was about 2.8×10^{-12} cm^2/device. The calculated SEL error rate averaged from the orbit for the VATA160 was 2.178×10^{-5}/device/day. Error rates in the worst-case analysis were 1–3 orders of magnitude higher than the averaged one. These calculated results provide important references for assessments of the anti-radiation capability of the device.

Acknowledgements We thank Institute of Modern Physics, Chinese Academy of Sciences (IMPCAS), and the China Institute of Atomic Energy (CIAE).

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