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journal or publication title	Microelectronics reliability
volume	64
page range	502-506
year	2016-09-18
URL	http://hdl.handle.net/10228/00006907

doi: info;doi/10.1016/j.microrel.2016.07.114

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Abstract

This paper discusses the universal calculation method for space proton induced failure rate on high power device. High energetic particles can be the reason of power device failure in both terrestrial and space. T-CAD simulation result gives a threshold charge value for the device destruction which is triggered by energetic proton from space. The amount of threshold charge depends on applied voltage for high power device. The probability of charge generation in silicon due to proton penetration is considered as well. This probability function variation depends on the thickness of device and incident energy of proton which studied before at there. Last consideration on this paper is 3.3 kV PiN diode's single event upset cross section and failure rate which was calculated by proposed method in Low earth orbit environment condition.

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Failure Rate Calculation Method for High Power Devices in Space Applications at Low Earth Orbit

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1. Introduction

Space industry market and manufacturing have been increased for last decades. Furthermore, this trend seems will be increased as well [1]. In order to implement large-scale space platforms, such as space station, big satellites, power generation will soon reach to the level of Megawatt [2-3]. Total power is gradually increasing as shown in the last twenty years its trend as well. (See Fig. 1)

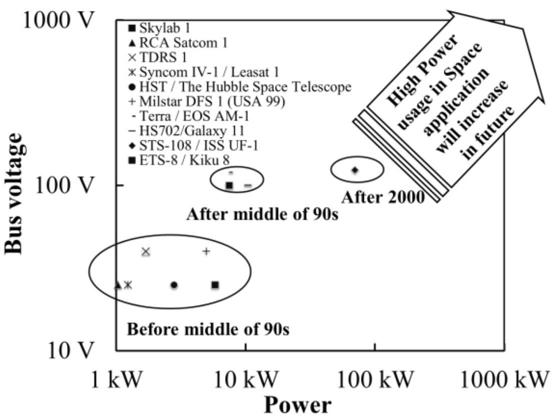

Fig. 1. Satellite's power generation trend.

Consequence of power increasing in space platform is harness mass increases, which relate to the budget issue of space technology. Relation between harness mass and power of satellite was studied (see Fig. 2) [4] and bus voltage increase will be the requirement for future space platforms.

The main idea of research is based on needs of high power demand on future space applications. It calls for high voltage generation and transmission since minimize the energy loss during power transmission and the cable mass. High voltage usage can be the mitigation of harness mass increase.

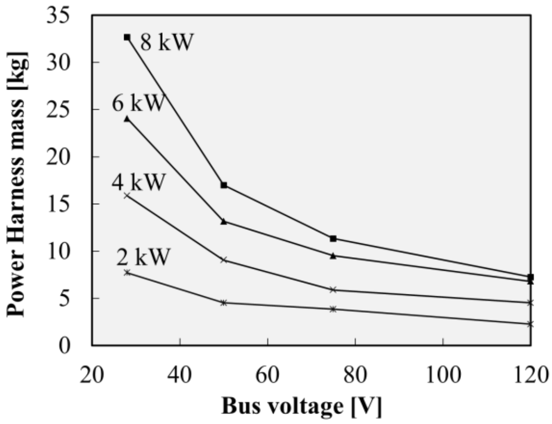

Fig. 2. Relation between harness mass and power of satellite.

The well-known studies have been shown that the cosmic ray penetration in semiconductor device is the failure which basically named "single event upset" (SEU) [5]. The failure induces by space proton is the one of problem; however we can generate high voltage in space. As studies shown, high power device failure due to space particles occurs in both space and terrestrial [6-8].

This research mostly related to the high voltage power semiconductor reliability in space application, especially proton, and its universal calculations formula proposal. Paper content consists of introduction, goal of research, methodology, result and conclusion.

2. Goal of the research

First of all, reliability of high power device for space application have to be evaluated somehow, in order to mitigate issues of its. In space most of

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failures of electronic devices are occurred due to the single event upsets through cosmic rays. 90% of those cosmic rays consist of protons [9] in low Earth orbit (below an altitude of 2000km). For that reason this paper assumed proton flux as a main flux function related to SEU. (Neutron flux is dominated in terrestrial; in spite of space proton flux is higher than other space particles [10]).

In our study, we proposed that failure rate calculation of power devices' main formula which based on SEU Cross section and Space proton flux function. Difference from SEU cross section for small signal semiconductor devices, the SEU cross section for high voltage power semiconductor depends on applied voltage.

The cross section is calculated by two functions, threshold charge to destruction $Q_{dest}(V)$ obtained by TCAD simulation (See Eq. 1) and charge generation probability function $\Phi_{Ep}(Q)$. By convoluting proton flux function with the SEU cross section function, the main failure rate calculation formula was derived (See Eq. 2).

$$\sigma(V) = A * \int_{Q_{dest}(V)}^{Q_{max}} \Phi_{E_p}^{300}(Q)\partial Q \quad (1)$$

$$FR = \int_{E_p^{min}}^{E_p^{max}} A * \int_{Q_{dest}(V)}^{Q_{max}} \Phi_{E_p}^{300}(Q)\partial Q * F(E_p)\partial E_p \quad (2)$$

Here:

FR - failure rate of device [s^{-1}]

A - Device area [m^2]

E_p - Incident energy of proton [MeV]

E_p^{max} -Maximum incident energy of Proton [MeV]

E_p^{min} - Minimum incident energy of Proton [MeV]

Q -Generated charge inside silicon by deposited energy [C]

Q_{max} - Maximum generated charge inside of silicon by deposited energy [C]

$Q_{dest}(V)$ -Threshold charge which can generate avalanche phenomena inside silicon due to deposited energy from proton [C]

$\Phi_{Ep}^{300}(Q)$ - Probability function of charge generation according to incident energy [C^{-1}]

$F(E_p)$ - Space proton flux funtion, which consists three sections by energy range at Low Earth Orbit [$MeV^{-1}s^{-1}m^{-2}$]

$\sigma(V)$- Single Event Upset Cross section [m^2]

In order to establish our proposed formula, three sections were considered. First, T-CAD device simulation, 3.3kV PiN diode was chosen for device model. Hence, destruction charge value, which is generated by deposited energy of space proton, was obtained from simulation. Second, Space proton flux data according to energy range in Low Earth Orbit (LEO), was obtained from SPENVIS web based software from European Space Agency, Alpha Magnetic Spectrometer (AMS) [11] and PAMELA data [12]. Third, probability function of energy deposition in device because consequently silicon-proton reaction and SEU cross section were studied before [13-16], from here, probability functions of energy deposition corresponding to device's applied voltages were calculated. Last result was defined as SEU cross section and failure rate respect to the applied voltage for 3.3 kV PiN diode. Details will be explained in next section.

3. Methodology

3.1. T-CAD Simulation

In T-cad simulation, energetic particle penetrated 3.3 kV PiN diode model was chosen (See Fig. 3); because simple structure of PiN diode can basically represent other semiconductor power devices. The transient simulation was performed on default value of most characteristics of model, . Total thickness of the model in simulation is 350 µm, but 300 µm thicknesses were assumed our calculation based on literature material that we found. Reverse bias Characteristics has been inputted in simulation (See Fig. 4).

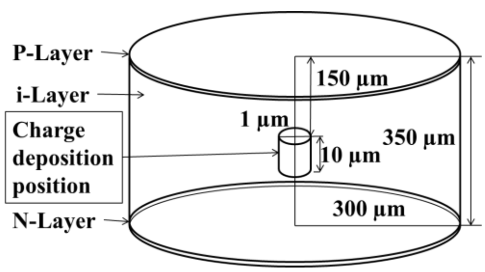

Fig. 3. Charge deposited 3.3 kV PiN diode model in T-CAD simulation.

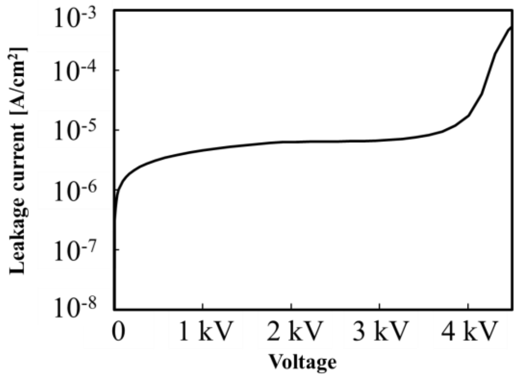

Fig. 4. Reverse bias Characteristics of 3.3kV PiN diode model for T-CAD simulation.

Purpose of simulation is to obtain destruction charge value prediction, which can be reason of SEU in device. When charged particles penetrate to the silicon, it generates amount electron-hole pairs, which can be trigger of avalanche phenomena in power device. It also strongly depends on applied voltage [6].

However heavy ion model were used for this simulation, it can gives properly destruction charge value function. Because avalanche phenomena can be occur as long as charge generates by any charged particles inside silicon. No matter particle is either heavy ion or proton. One of result shows avalanche phenomena which triggered by energetic particle (See Fig. 5) and it seems similar to studies [7].

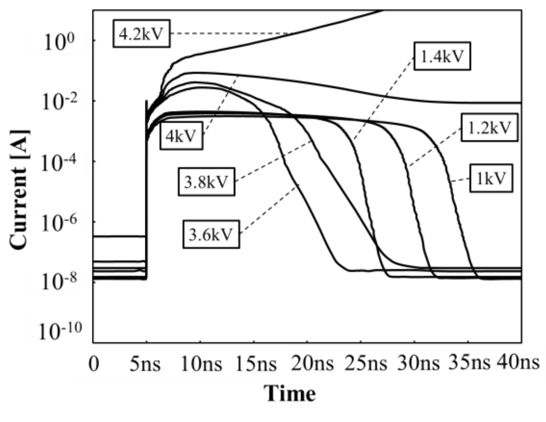

Fig. 5. Current waveform through PiN diode after depositing charge of 10 pC inside the device.

Then values of charge generations by diverse energy of heavy ion case were obtained from simulation (See Fig. 6).

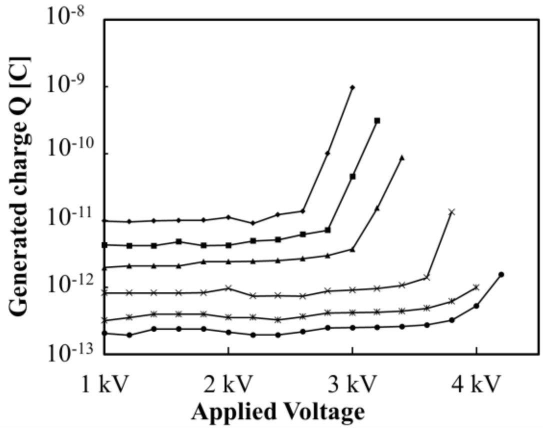

Fig. 6. Charge generation as a function applied voltage obtained from TCAD transient simulation (ex. see Fig. 5) for different deposited charge in 3.3kV PiN diode.

Here we can gather destruction charge values which can be trigger of avalanche phenomena. Based on these results, fitting function for destruction charge and applied voltage dependence were built (See Fig. 7). Value of this function written as $Q_{dest}(V)$ in main formula.

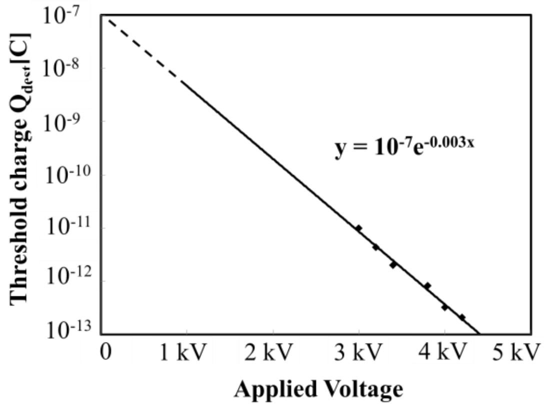

Fig. 7. Destruction charge values, which is generated by deposited energy to the silicon from penetrated space proton and its fitted function.

3.2. Proton flux data

As mentioned before, majority of cosmic ray consists of proton in Low Earth Orbit [9]. Trapped proton flux, solar proton flux, and cosmic proton flux compound total space proton flux at Low Earth Orbit. However proton flux density is not uniformly dispersed along the Low earth orbit, in the main formula, total space proton flux written as fitted function $F\ (E_p)$ which doesn't depend on orbital position. In calculation, shield material hasn't been considered. It may affect last result.

Entire energy range of considered proton flux divided three sections. First 1MeV-400MeV proton flux data, which considered at 700 km altitude and its fitted function were taken from SPENVIS web based software was developed by European Space Agency (See Fig. 8) [19], here mission period assumed 2018-2019, that could clarify sun activation. Second 1GeV-20GeV proton flux data, which measured at around altitude of 350-610km and its fitted function were taken from PAMELA data source (See Fig. 9) [11]. At last 20GeV-200GeV proton flux data, which measured at altitude of International space station around 400 km and its fitted function were taken from AMS data source (See Fig. 10) [12]. These three fitted functions were used for calculation.

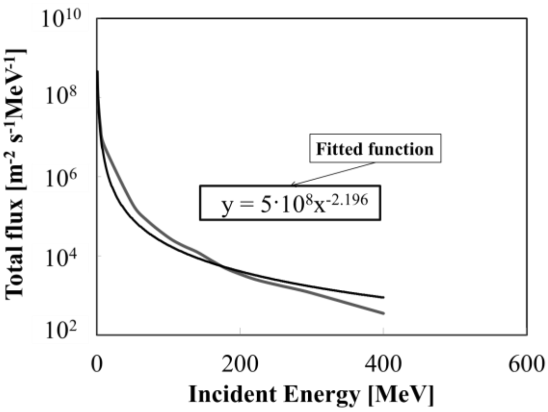

Fig. 8. 1-400 MeV proton flux data at in LEO /SPENVIS around 700 km altitude/ and its fitted function.

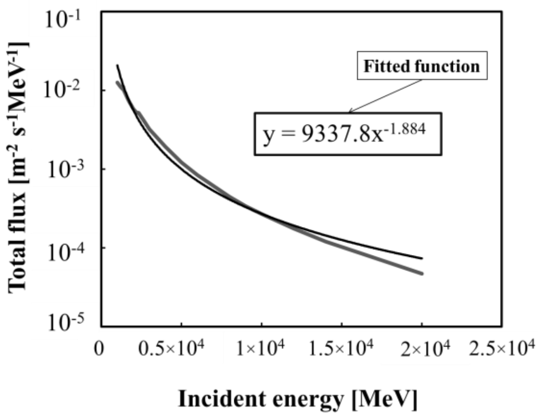

Fig. 9. 1GeV-20GeV proton flux in LEO /PAMELA 350km-610km altitude/ and its fitted function.

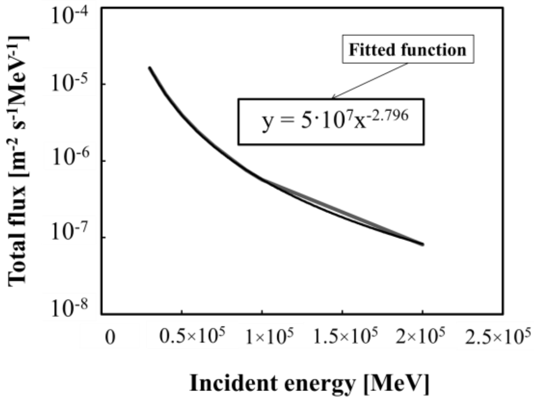

Fig. 10. 20GeV-200GeV proton flux in LEO/AMS around 400km altitude/ and its fitted function.

3.3. Probability function fitting

This section purpose is to derive probability function of charge generation $\Phi_{Ep}^{300}(Q)$ by energetic proton. We assumed that, deposited energies form protons to the silicon completely generate electron-hole pairs. On the other hand amount of generated charge linearly depends of deposited energy. Pair generation energy depends on the medium band gap energy. In silicon case the average energy E_g required to create an e-h pair in silicon is $E_g \approx 3.68$eV. The pair charge is e=1.6x10^{-19}C [17]. Hence coefficient α=2.33×10^{13}MeV/C, which shows relation between deposited energy and generated charge has been found.

The existing study defined probability function of energy deposition based on HETC calculation (See Eq. 3) [13-16].

$$\Phi_{Ep}^{x}(E_d) = 10^{a_1(E_p^x)E_d + a_0(E_p^x)} + 10^{b_1(E_p^x)E_d + b_0(E_p^x)} \quad (3)$$

$$\Phi_{Ep}^{x}(E_d) = \Phi_1(E_d) + \Phi_2(E_d)$$

Here:
E_d - Deposited energy [MeV]
x - Sensitive thickness [µm]
Φ_1 - Probability function for low energy deposition [MeV^{-1}]
Φ_2 - Probability function for high energy deposition [MeV^{-1}]
b_1 - Parameter according to high energy deposition
b_0 - Parameter according to probability

Basically, we can say that energy deposition function consists of two decreasing exponential functions and Φ_1 correspond to E_d < 2 MeV energy of particles, Φ_2 correspond to higher energy of particles [13]. In our calculation Φ_2 is important, and then Φ_1 omitted. In order to define Φ_2, we need to Fig.ure out b_1 and b_0. Parameters depend on sensitive thickness of silicon and incident energy of particles. Our model defined device thickness as around 350μm and on the other hand generally device thickness is around 300μm therefore sensitive thickness has been fixed on 300μm. Parameters b_1 and b_2 found from the paper as well [13]. Parameter b_1 at 19μm sensitive thickness defined at the paper [14]. By combining these two data, fitted functions for b_1 and b_0 were obtained (See Fig. 11, Fig. 12).

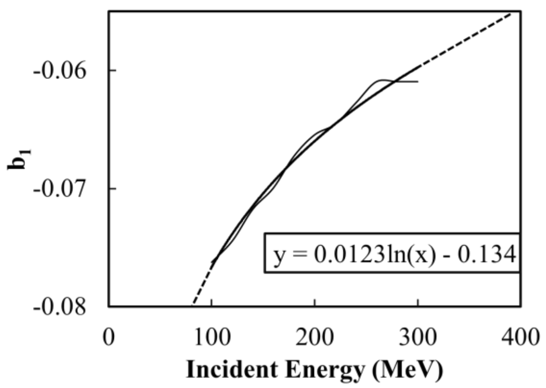

Fig. 11. Fitted b_1 (at 300 μm Si).

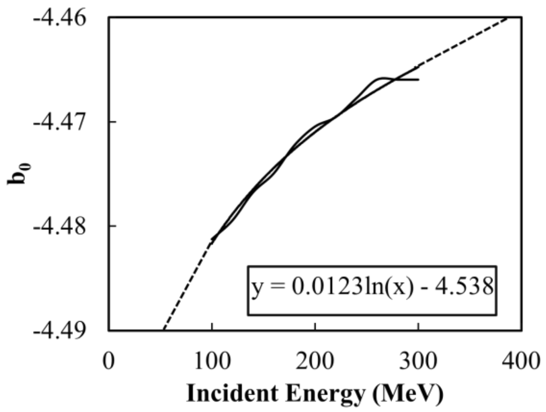

Fig. 12. Fitted b_0 (at 300 μm Si).

Hence probability function of energy deposition $\Phi_{Ep}^{300}(E_d)$ has been defined at 300μm thickness (See Eq. 4). Here probability function defined by deposited energy, last purpose is to define probability function by generated charge. We used α coefficient for transition under the relation $E_d = \alpha \times Q$, $\Phi_{Ep}^{300}(E_d)$ to $\Phi_{Ep}^{300}(Q)$ as using expression $\Phi_{Ep}^{300}(E_d) = \Phi_{Ep}^{300}(\alpha \times Q)$. Probability function which defined by generated charge has been found (See Eq. 5).

$$\Phi_{Ep}^{300}(E_d) = 10^{b_1(E_p^x)E_d + b_0(E_p^x)} \tag{4}$$

$$\Phi_{Ep}^{300}(\alpha Q) = 10^{b_1(E_p^x)\alpha Q + b_0(E_p^x)} \tag{5}$$

Using above relation we made transition from probability function of deposited energy $\Phi_{Ep}^{300}(E_d)$ to probability function of generated charge $\Phi_{Ep}^{300}(Q)$, and for simplicity we used same notation Φ_{Ep}^{300} for both functions.

4. Result

By combining above three sections on the main formula, last results were obtained. Result include two characteristics, one is the 3.3 kV PiN diode's Single Event Upset Cross Section respect varying applied voltages, which can used for any proton flux of environment (See Fig. 13). This result seems similar to existing data on literature [18].

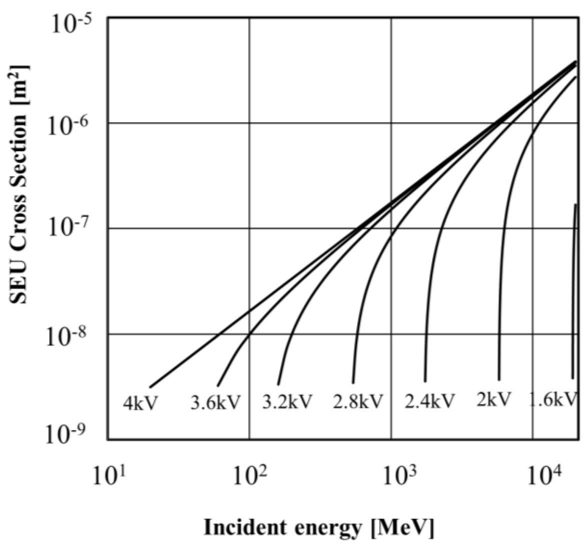

Fig. 13. SEU Cross section VS Incident energy of Proton dependence at various applied voltages (3.3kV PiN diode, Area=10^{-4} m^2, 10MeV-20GeV).

The failure rate prediction calculated by proposed method for 3.3 kV PiN diode in Low Earth Orbit condition is shown as below (See Fig. 14).

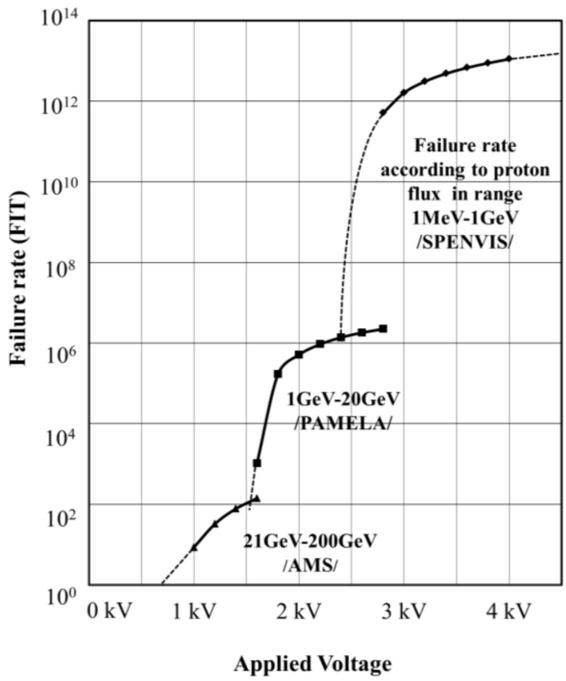

Fig. 14. Failure rate VS Applied voltage in Low Earth Orbit (3.3kV PiN diode, Incident energy range 1MeV-200GeV).

5. Conclusion

We established method that consists of Destruction charge values from T-cad simulation, proton flux data and probability of energy deposition due to proto-silicon interaction from literature. From the result we can see that failure rate is apparently higher than terrestrial region case (assumed terrestrial FIT=1).

By using Single Event Upset cross section $\sigma(V)$, that we obtained can be used for any proton flux of environment. PiN diode model can be changed by any other power semiconductor devices.

Proposed method can contribute to mitigate failure for high power devices' usage and predict space application's MW range of power systems reliability in future.

Note: In this study, T-cad simulation electric field, that can affected by proton hitting position in silicon, was fixed. Further, electric field dependence will be assumed. Crystal degradation due to space radiation was not considered as well. One more thing is that we didn't consider shield material in space equipment. This can be the reason of high failure rate that we predicted.

6. References

[1] Ethan E. Haase, Carissa Bryce Christensen, Hans Ten, Cate Global Commercial Space Industry Indicators and Trends. In: Acta Astronautica, 2002, Vol. 50, No. 12, pp. 747–757.

[2] John R. Brophy, Robert Gershman, Nathan Strange, Damon Landau, 300-kW Solar Electric Propulsion System Configuration for Human Exploration of Near-Earth Asteroids. In: 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2011, AIAA 2011-5514.

[3] Mengu Cho, Akiyo Saionji, Kazuhiro Toyoda, Masayuki Hikita, High Voltage Solar Array for 400V Satellite Bus Voltage: Preliminary Test Results. In: 41st Aerospace Sciences Meeting and Exhibit, 2003, AIAA 2003-683.

[4] Kitt C. Reinhardt, Clay S. Mayberry, Dave S. Glaister, Space Power Technology in Power Management and Distribution Electronics. In: Journal of Spacecraft and Rockets. November–December 1998, Vol. 35, No. 6.

[5] W.L. Bendel, E.L. Petersen, Proton Upsets In Orbit. In: IEEE Transactions on Nuclear Science, 1983, Vol. NS-30, No. 6.

[6] W. Kaindl, G. Solkner and G. Wachutka, Analysis of charge carrier multiplication events in NPT and PT-diodes triggered by an ionizing particle. In: Electron Devices and Solid-State Circuits, IEEE Conference on, 2003, pp. 383-386.

[7] Gerald Soelkner, Peter Voss, Winfried Kaindl, Gerhard Wachutka, K. H. Maier, H.-W. Becker, Charge Carrier Avalanche Multiplication in High-Voltage Diodes Triggered by Ionizing Radiation. In: IEEE Transactions on Nuclear Science, December 2000, Vol. 47, No. 6.

[8] A.M. Albadri et al., Single event burnout in power diodes: Mechanisms and models. In: Microelectronics Reliability, Volume 46, Issues 2–4, February–April 2006, Pages 317-325.

[9] M. Ackermann et al., Detection of the Characteristic Pion-Decay Signature in Supernova Remnants. In: Science Magazine, 2013, volume 339, page 807.

[10] J. F. Ziegler, Terrestrial cosmic rays, In: IBM Journal of Research and Development, Jan. 1996, vol. 40, no. 1, pp. 19-39.

[11] M. Aguilar et al., Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station. In:, Phys. Rev. Lett. April 2015, 114, 171103.

[12] O. Adriani et al., PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra. In: Science, Apr 2011, Vol. 332, Issue 6025, pp. 69-72.

[13] B. Doucin et al., Characterization of proton interactions in electronic components. In: IEEE Transactions on Nuclear Science, Jun 1994 vol. 41, no. 3, pp. 593-600.

[14] B. Doucin, T. Carriere, C. Poivey, P. Garnier, J.

Beaucour, Y. Patin, Model of single event upsets induced by space protons in electronic devices. In: Radiation and its Effects on Components and Systems, 1995. RADECS 95., Third European Conference on, Arcachon, 1995, pp. 402-408.
[15] K. Kwiatkowski, S. H. Zhou, T. E. Ward, V. E. Viola, Jr., H. Breuer, G. J. Mathews, A. Gökmen, A. C. Mignerey, Energy Deposition in Intermediate-Energy Nucleon-Nucleus Collisions. In: Phys. Rev. Lett. 1983, 50, 1648.
[16] T. A. Gabriel, The High Energy Transport Code, HETC. In: Proceedings of the LEP Experimenters' Workshop on Shower Simulation, In: CERN, Geneva, Switzerland, January 29-31, 1985.
[17] R. C. Alig, S. Bloom, C. W. Struck, Scattering by ionization and phonon emission in semiconductors. In: 1980, Phys. Rev. B 22, 5565.
[18] W. J. Stapor, J. P. Meyers, J. B. Langworthy and E. L. Petersen, Two parameter Bendel model calculations for predicting proton induced upset [ICs]. In: IEEE Transactions on Nuclear Science, Dec 1990, vol. 37, no. 6, pp. 1966-1973.
[19] https://www.spenvis.oma.be/ :1997-2015, ESA