Failure rate calculation method for high power devices in space applications at low earth orbit

Erdenebaatar Dashdondog[1,*], Shohei Harada[2], Yuji Shiba[2], Masaki Sudo[2], Ichiro Omura[2]

[1]*Department of Physics, National University of Mongolia, Ulaanbaatar, Mongolia*

[2]*Department of Electrical Engineering and Electronics, Kyushu Institute of Technology*

In this paper we propose that calculation method to evaluate failure rate of high power semiconductor device against proton flux environment of low earth orbit. Advantage of this method is to expand to evaluate failure rate of any devices under various radiation environment. Possible suggestion to improve high power device reliability was discussed.

Nomenclature

FR	:	Failure rate (FIT)
α	:	Convert from energy to charge
$\sigma(V)$	:	Cross section (cm^2)
$F(E_p)$	:	Flux of particles ($MeV^{-1}s^{-1}cm^{-2}$)
E_p	:	Particle incident energy (MeV)
A	:	Device area (cm^2)
$\Phi_{Ep}(Q_g)$	:	Probability function for generated charge ($C^{-1}\mu m^{-1}$)
Q_g	:	Generated charge (C)
$Q_{dest}(V)$	:	Threshold charge to destruction (C)
$W(Eg)$	:	Energy to generate a pair (eV)

I. INTRODUCTION

Space industry market and manufacturing have been increased for last decades. Furthermore, this trend seems will being increased [1]. In order to implement large-scale of space platforms, such as space station, big satellites' power generation will soon reach to the level of Megawatts [2,3]. Last decades spacecraft power demand is shown in Fig. 1. Consequence of power demand increasing leads to the harness mass increasing of spacecraft. Harness mass is approximately 8% of spacecraft dry mass [4].

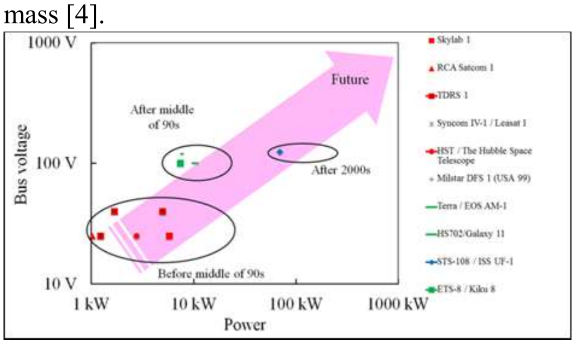


Fig. 1. High Power and Voltage in Space applications for last decades.

Relation between harness mass and power demand of spacecraft was studied [5] and is shown in Fig. 1. For instance if the bus voltage increase by 100V, then harness mass reduction would be 75% of initial mass. Hence it seems that bus voltage increase will be the requirement for future space platforms. By using high voltage in bus system of spacecraft, there is a risk to destruct that power device due to the energetic particle penetration from the space. The well-known studies have been studied this failure which basically named "single event burn out for power devices and other electronics [6]. In order to mitigate that risk, evaluate reliability then failure rate should be investigated against space environment. Proton flux is the majority of energetic particle flux at low earth orbit. Therefore this paper proposes and discusses method for space proton induced failure rate on high power device. The proposed method could be developed to be able to calculate failure rate of any power device under space radiation in various altitude. We selected low earth condition as target of this particular paper. Besides, high energetic particles can be the reason of power device failure in both terrestrial and space [7, 8, 9].

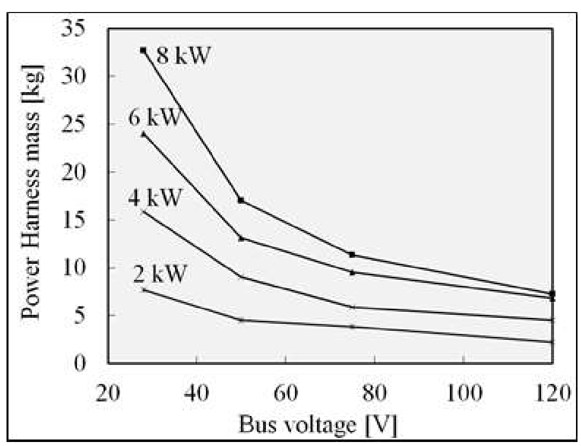


Fig. 2. Relation between harness mass and power of satellite.

* Electronic address: erdenebtr@gmail.com

II. PROPOSED METHOD TO CALCULATION OF FAILURE RATE

The main formula of proposed method in this study is expressed by Eq. (1) and consists of three sections as shown in Fig. 3. First, TCAD simulation, its result gives a threshold charge value for the device destruction, at various applied voltages case, which is triggered by energetic proton from space. The amount of threshold charge depends on applied voltage for high power device. Second, there is a probability of charge generation in silicon due to proton penetration. This probability function's variation depends on the thickness of device and incident energy of proton. This function was defined before at library. Third consideration on this study is space proton flux data at low earth orbit which has been provided by astrophysics studies, assumed energy range of proton flux is 1MeV to 200GeV. Simulated device model was 3.3 kV PiN diode.

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

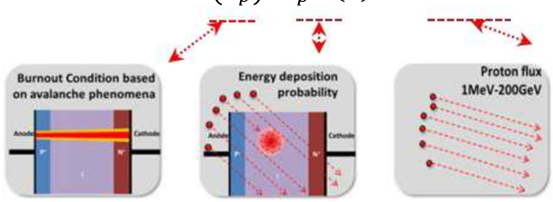


Fig. 3. Compounds of proposed formula.

The Single event burnout cross-section of PiN diode has been calculated by equation (2) and failure rate of it has been calculated by proposed method at Low earth orbit environment condition

$$\sigma(V) = A * \int_{Q_{dest(V)}}^{Q_{max}} \Phi_{E_p}^{300}(Q)\partial Q \qquad (2)$$

III. PROPERTIES OF COMPOUND PARAMETERS

A. Threshold generated charge to destruction $Q_{dest}(V)$

In T-cad simulation, heavy ion injected 3.3 kV PiN diode model was chosen; due to that basic structure of PiN diode can represent other semiconductor power devices. The default value of most variables of model was used for the transient simulation performance. The $Q_{dest}(V)$ was obtained from TCAD simulation for case of 3.3-kV PiN diode. The simulated cylindrical structure model is shown in Fig. 4. Radius is 400 µm. High doped N-layer, P-layer and light doped 350 µm of N-base layers were compounds of the model. When proton penetrates semiconductor device, it generate secondary recoiled heavy ion which can make ionization. Recoiled proton transfer small amount of energy to the silicon. Hence we can assume that heavy ion model represents proton induced charge generation in the semiconductor device. Place that heavy ion injected is the center of horizontal axis and has 10 µm of length of track below P-layer along to the N-base. The generated charge Q_g track has radial Gaussian distribution determined by length of 0.02 µm.

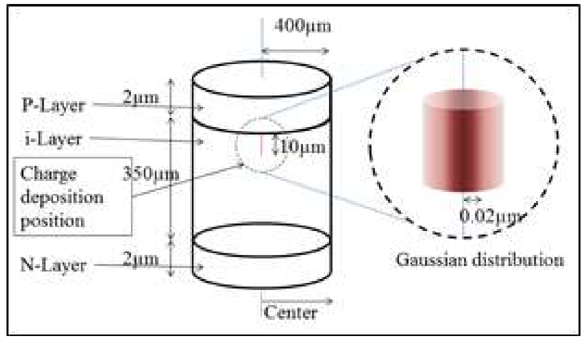


Fig. 4. Charge deposited 3.3 kV PiN diode model in T-CAD simulation.

When the generated charge Q_g becomes larger than certain amount, then avalanche phenomenon starts. The value of generated charge Q_g that triggers avalanche phenomenon starting was determined as the threshold charge to destruction $Q_{dest}(V)$, which has a function of the applied voltages.

From Fig. 5 we can see that the Electron current density spatial distribution after 250ps of 100MeV of heavy ion injection when applied voltage was varied. Hence we can apparently assume that Q_g is directly proportionally depended on the applied voltage. The increase of Q_g is occurred due to the charge multiplication avalanche phenomenon in the silicon semiconductor devices[10,11]

The avalanche phenomenon needs to have certain amount of charge to trigger itself. Threshold charge which can generate avalanche phenomenon was main target of TCAD simulation. We obtained values of threshold charge to destruction $Q_{dest}(V)$ from 10 MeV, 50 MeV and 100 MeV of energy of heavy ion injection cases. $Q_{dest}(V)$ function has been derived as shown in Fig. 6.

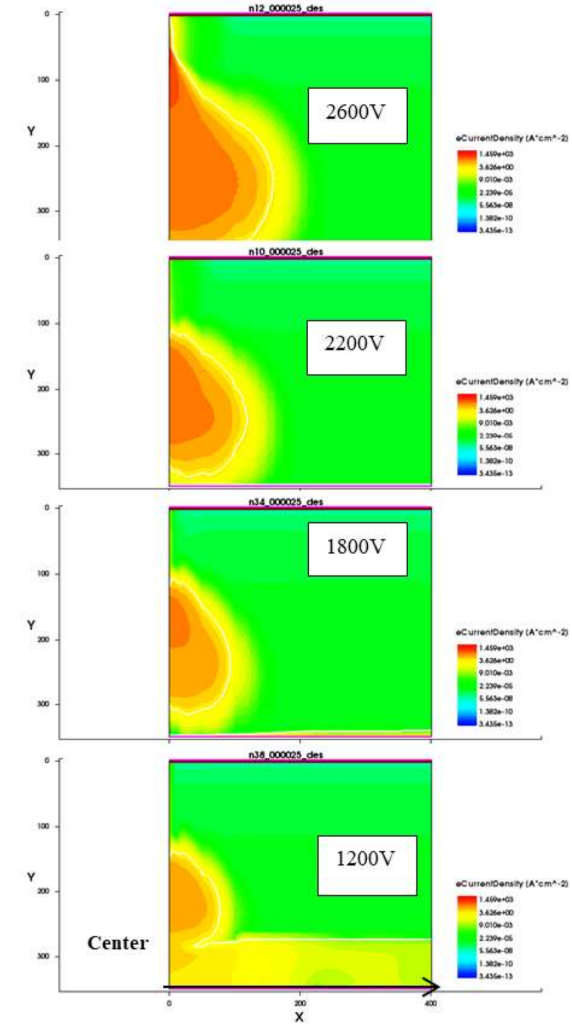


Fig. 5. Electron current density spatial distribution after 250ps of 100MeV of heavy ion injection when applied voltage was varied.

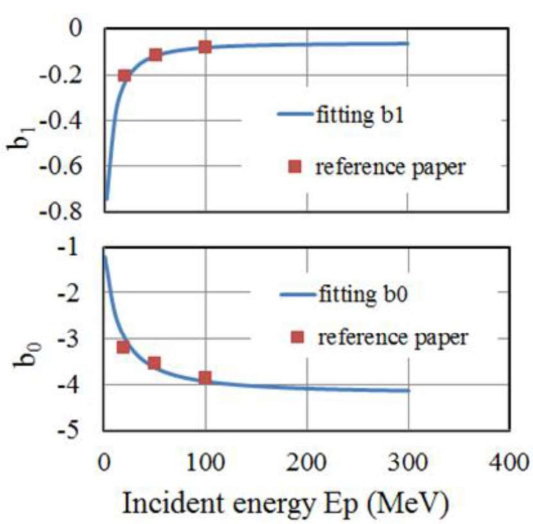


Fig. 6. Fitted b1 and b0 (at 300 µm Si).

Here we can see that $Q_{dest}(V)$ of TCAD result was basically matched with reference data and its fitted function obtained as well.

B. Probability function for deposited charge $\Phi_{Ep}(Q_g)$

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. The energy $W(E_g)$ required to create an e-h pair in a semiconductor by a charged mass particle traversing the medium depends on the band gap energy Eg of the material and hence, although only slightly, on the temperature. The measurements of this quantity show a nearly linear dependence on the band gap energy, and the linear fit to the data obtained for different materials gives Eq. (3).

$$W(Eg) = 1.76\ eV + 1.84 Eg\ eV \quad (3)$$

The mean energy W(Eg) to create an electron-hole pair has been calculated and measured in experiments including high energy charged particles. The mean energy $W(E_g)$ required to create an e-h pair in silicon is $W(E_g) \approx 3.68$ eV. The pair charge is e=1.6*10-19 coulomb [12]. Hence coefficient α=2.33×1013MeV/C, which shows relation between deposited energy and generated charge has been found.

In order to define proton cross section, literature study was used [13, 14]. In this that referenced paper, the modeling of proton single event phenomena cross-sections versus proton kinetic energies is based on the fact that secondary recoils induced by proton Silicon nuclear reactions are mainly responsible for the devices destruction. The proton energy loss in matter is too low (several keV/pm) to generate Single Event burnout directly. The secondary recoil energies, ranging from several keV to several MeV, are comparable to the energies lost by primary heavy ions crossing the devices. The referenced model, developed to define proton cross section in silicon, assumes that the semiconductor element will react similarly as long as the amount of energy Ed is provided by a proton Silicon nuclear reaction or by an energetic heavy ion. Using this referenced study result [13,14], we can obtain proton energy deposition probability function $\Phi_{E_p}^{300}(E_d)$ which is at case of 300µm of thickness of silicon as shape that shown in Eq. (4). We assumed that all energy transferred to silicon is completely generated charge in silicon as expressed in Eq. (5). The relation between charge generation probability and energy deposition probability is expressed in Eq. (6). Apparently, charge generation probability function as expressed in Eq. (7) is derived.

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

$$E_d = \alpha Q_g \quad (5)$$

$$\Phi_{E_p}^{300}(E_d) = \Phi_{E_p}^{300}(\alpha Q_g) \quad (6)$$

$$\Phi_{E_p}^{300}(\alpha Q_g) = 10^{b_1(E_p^x)\alpha Q_g + b_0(E_p^x)} \quad (7)$$

In order to define $\Phi_{E_p}^{300}(\alpha Q_g)$ then b_1, b_0 should be expressed by function of incident energy of proton flux. Based on literature study [13,14,15,16], parameters b_1, b_0 were defined as shown in Fig. 7

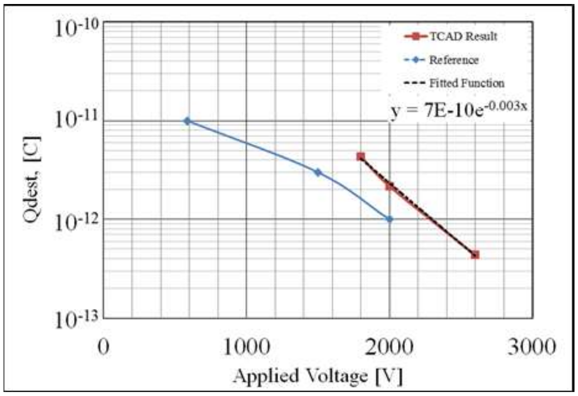


Fig. 7. Relationship between threshold generated charge to destruction Qdest(V) and applied voltage.

In this function we assumed silicon thickness was 300μm. The typical power devices semiconductor thickness equals to around 300μm.

Hence we can obtain fitted mathematical functions of b_1 and b_0 for the Eq. (7) as shown in Eqs. (8) and (9).

$$b_1(300, E_p) = \frac{-100}{(E_p+15)^{1.8}} - 0.063 \quad (8)$$

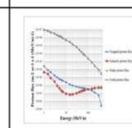
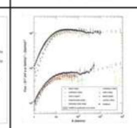
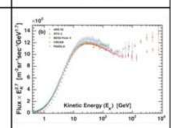
$$b_0(300, E_p) = \frac{200}{(E_p+20)^{1.38}} - 4.2 \quad (9)$$

C. Proton flux data *F(E_p)*

Most of portion of cosmic ray is proton in Low Earth Orbit [17]. Entire energy range of considered proton flux divided three sections which are in range of 1Mev-200GeV as shown in Table 1. Firstly, 1MeV-400MeV proton flux data corresponding to 700 km altitude was taken from SPENVIS [18] and that accounted sun activation. SPENVIS is the web based software was developed by European Space Agency and is widely used space application studies, here mission period assumed 2018-2019.

Second 1GeV-20GeV proton flux data, which measured at around altitude of 350-610km were taken from PAMELA [19] data source. PAMELA is the spacecraft mission payload for study about possible exotic cosmic ray source and its propagation reasons; mission time was 2006-2008. Proton is top set of data. Helium is the bottom set of data. Thirdly, 20GeV-200GeV proton flux data, which measured at altitude of around 400km, were taken from AMS data source. AMS is a general purpose high energy particle physics detector in space[20]. Fitted functions for these data were used for calculation.

Table 1 Entire energy range of considered proton flux divided three sections which are in range of 1Mev-200GeV.

Source of data	1. SPENVIS	2. PAMELA	3. AMS
Methods	Simulation	On orbit Experiment	On orbit Experiment
Considered Particles	Proton	Proton	Proton
Energy range	1-400MeV	1GeV-20GeV	20GeV-200GeV
Altitudes	~700km	~610km	~400km
Plots			
References	https://www.spenvis.oma.be/	O. Adriani, "PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra," Science, vol. 332, no. 6025, pp. 69-72, Apr 2011.	Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station," Physical review letters, vol. 114, pp. 171103-1, May 2015.

From these data fitted functions depending incident proton energy can be written in low, medium and high range of energy levels as shown in Eqs. 10, 11 and 12. Shielding effect was accounted during calculation.

$$E_p^{Low}(E_p) = 5 \cdot 10^8 \cdot (E_p)^{-2.196} \quad (10)$$

$$E_p^{Med}(E_p) = 9337.8 \cdot (E_p)^{-1.884} \quad (11)$$

$$E_p^{High}(E_p) = 5 \cdot 10^7 \cdot (E_p)^{-2.796} \quad (12)$$

IV. RESULT

As combining above functions, we calculated failure rate of 3.3 kV PiN diode at low earth environment condition was calculated and its result shown in the Fig. 8. Here, two types of dotted lines represents failure rate of 3.3kV pin diode, corresponding to case of shielded and unshielded condition. Shielding material is 0.1 in of Aluminum. Shielding function obtained from literature [21]. As seeing this result aluminum shielding could not be proper protection against proton flux. The red dashed line represents FIT=1(one failure in 10^9hours) that typically used for power device's allowed failure rate for commercial application [22]. In this case, as seeing the result, application voltage of 3.3kV diode should be approximately 1.5kV for space application. The blue line represents power devices failure rate at terrestrial. Comparing results, space applications power semiconductor devices failure rate is higher than terrestrial failure rate several magnitude.

V. CONCLUSION

In this paper 3.3kV PiN diode's proton induced single event burnout failure rate was calculated.

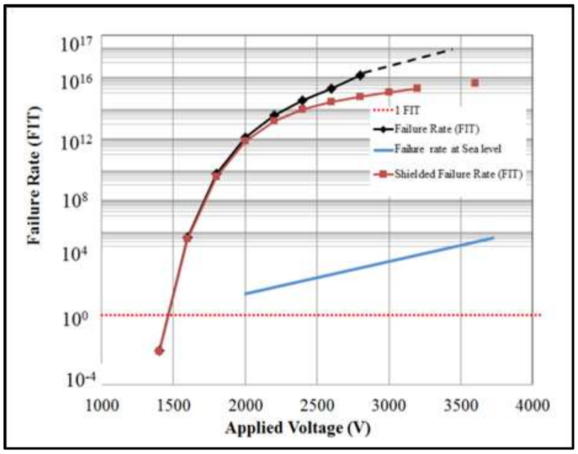


Fig. 8. Failure rate of 3.3kV PiN diode at Low Earth Orbit was calculated by proposed method.

The main formula which used for calculation compounds of three independent parts. Each part can be developed separately and it could be changed by other environment other devices. That means the proposed method for high voltage power devices failure rate calculation is feasible to diversity of any other power devices at any radiation environment. In further, using this flexible aspect of method, software application will be developed for radiation induced failure rate calculation of power devices.

REFERENCES

[1] Ethan E. Haase, Carissa Bryce Christensen, Hans Ten.: Cate Global Commercial Space Industry Indicators and Trends, 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, 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, 41st Aerospace Sciences Meeting and Exhibit, 2003, AIAA 2003-683.

[4] James R. Wertz, David F. Everett, Jeffery J. Puschell.: Space Mission Engineering: The New SMAD, Space Technology Library, Vol. 28, July 29, 2011

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

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

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

[8] 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, IEEE Transactions on Nuclear Science, December 2000, Vol. 47, No. 6.

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

[10] G. Sokner, G. Wachutka W. Kaindl.: Analysis of Charge Carrier Multiplication Events in NPT and PT-Diodes Triggered by an Ionazing Particle, Electron Devices and Solid-State Circuits IEEE, p. 383, 2003.

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

[12] S. Bloom, and C. W. Struck R. C. Alig.: Scattering by ionization and phonon emission in semiconductors, PHYSICAL REVIEW B, vol. 22, no. 12, 1980.

[13] B. Doucin et al.: Characterization of proton interactions in electronic components, IEEE

Transactions on Nuclear Science , vol. 41, no. 3, pp. 593-600, Jun 1994.

[14] B., Carriere, T., Poivey, C., Garnier, P., Beaucour, J., Patin, Y. Doucin.: Model of single event upsets induced by space protons in electronic devices, Proceedings of the European Conference on Radiation and its Effects on Components and Systems, RADECS, pp. 402-408, Sep 1995.

[15] Roberts, J. A.: Satellite Formation Flying for an Interferometry Mission, Ph.D. Thesis, Cranfield University, 2005.

[16] Kato, H.: Prediction of Wake Turbulence Behaviors Using Weather Observation and Simulation, Master's Thesis, Tohoku University, 2010 (in Japanese).

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

[18] https://www.spenvis.oma.be/:1997-2015, ESA

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

[20] 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, Phys. Rev. Lett. April 2015, 114, 171103.

[21] E. C. Smith.: Effects of Realistic Satellite Shielding on SEE Rates, IEEE Transactions On Nuclear Science. Vol. 41, No. 6, 2396, December 1994.

[22] H. R. Zeller.: Cosmic ray induced failures in high power semiconductor devices, Microelectronics Reliability, Vol. 37, No. 10-11, pp. 1711-1718, 1997.