人工衛星に使用するパワーデバイスの宇宙線耐量
Failure rate calculation method for power semiconductors for space application

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概要

パワー半導体の高性能化が進むにつれ、パワー半導体の宇宙線破壊が問題となり、1990 年代半ばに詳細に研究された結果、実験的に得られた設計カーブにより高信頼なデバイスの設計が可能になった。しかし最近、国際宇宙ステーションや人工衛星などの宇宙環境で用いる機器の消費電力が上昇し、電源の高電圧化が検討されているなかで、改めてパワーデバイスの宇宙線破壊が問題になってくる可能性が出てきた。

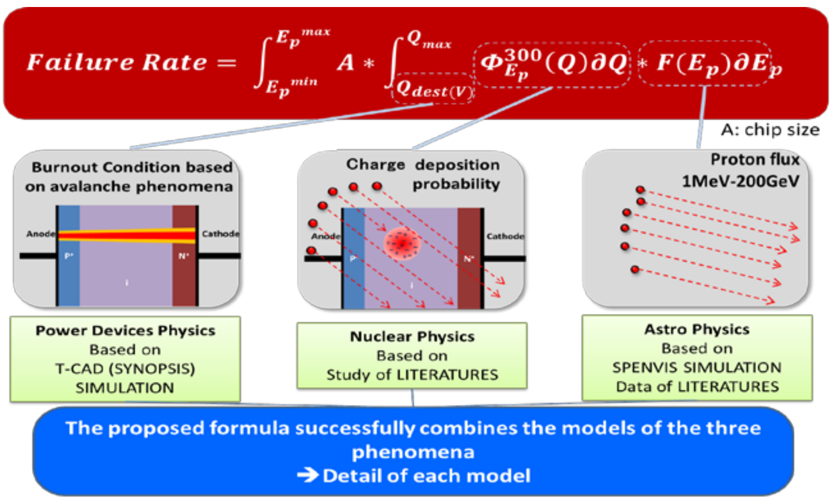
前述の地上でのデバイス利用を前提とした宇宙線破壊現象の解析では、地上での実験により検討を行うことができるため比較的容易に故障率の計算ができるようになっている。ところが宇宙利用の場合、高エネルギー粒子のエネルギーに対する確率分布（スペクトル）が異なるため、地上での実験結果を活用することができない。このため全く新しい、汎用的な故障率計算方法の確立が必須である。

本研究では、故障率の汎用計算式を導出し高エネルギー粒子のフラックス、高エネルギー粒子が発生する電荷の分布関数、さらに電荷が引き起こす破壊、の 3 つの観点から定式化を行い、それぞれの関数を人工衛星に関する研究論文、核物理に関する論文、さらに TCAD による破壊シミュレーションを組み合わせで求めた。さらに提案式で実際に低軌道人工衛星での 3.3 k V PiN ダイオードの故障率を計算した。

今回提案した手法では、パワーデバイスで初めて宇宙線破壊断面積（SEB cross section）の計算を可能にし、一度この関数が求まれば、あらゆる高エネルギー粒子のフラックススペクトルに対して容易に故障率を計算することができる。将来、この式をさらにブラッシュアップし、広く汎用的に使われるようにパラメータ関数の基礎データを集め、計算プログラムの確立していきたい。

本報告は、下記の博士論文の内容を説明したものである。

Erdenebaatar Dashdondog, “Failure Rate Calculation Method for High Voltage Semiconductor Devices under Space Radiation Environments” 九州工業大学　博士論文　2017



人工衛星に使用するパワーデバイスの
宇宙線耐量

九州工業大学
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ERDENEBAATAR DASHDONDOG

Outline

1. Introduction
   - ✓ Power Demand Increase in Spacecraft
   - ✓ Requirement of Bus Voltage Increase
   - ✓ Issues in High Voltage Power Device in Spacecraft
2. Cosmic Ray Induced failure in Power Device
   - ✓ Reason and mechanism
3. Failure Rate Calculation Formula for Space Use Power Device Design
   - ✓ Propose of General Formula for Failure Rate Calculation
   - ✓ High Energy Particle (Proton) Flux Distribution Function
   - ✓ Energy (Charge) Deposition Probability Density Function
   - ✓ Device Destruction Charge for Applied Voltage
4. Calculation Results for 3.3kV PiN diode for Low Orbit
5. Conclusions

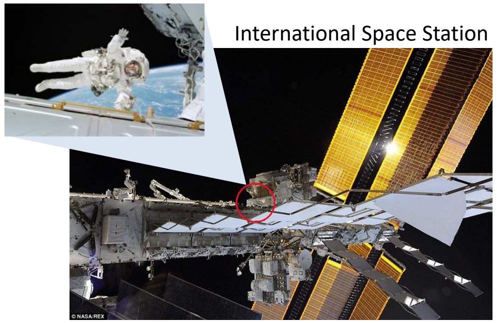
Power Demand in SPACE

Sputnik to International Space Station

SPUTNIK 1

http://officenaps.com/exoticaspace-age/the-space-race/attachment/jacknitzsche/

International Space Station



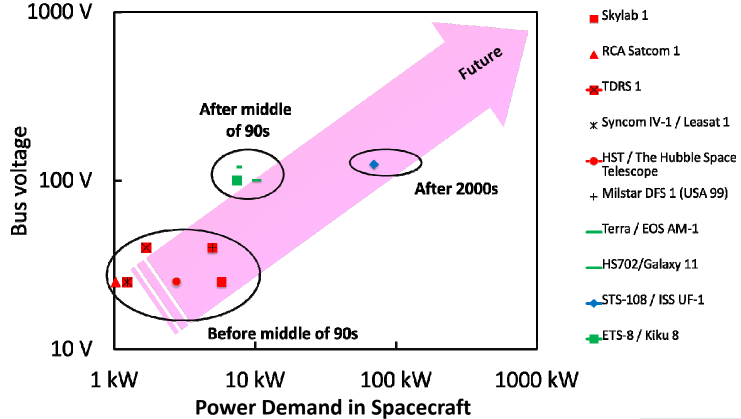
http://i.dailymail.co.uk/i/pix/2015/03/02/263F8ADB00000578-2976216-image-m-38_1425325704906.jpg

- ◆ Launch October 4, **1957**
- ◆ 83kg; bit bigger than soccer ball
- ◆ **Electrical Power ~1W**
- ◆ ~3 weeks

- ◆ Launch November 20, **1998**
- ◆ 419,455 kg; size of football field
- ◆ **Electrical Power up to 120 kW**
- ◆ ~18 years

Power demand has been tremendously increased

Power and Voltage in SPACECRAFT



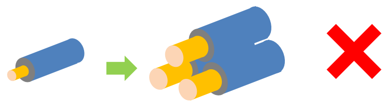
Power usage in Space application will exponentially increase in future
➔Bus voltage increase !!

$V \propto \sqrt{P}$
Means
1MW ∝ 1000V

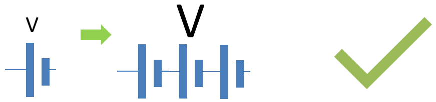
Consequence of Power Increase

In order to reduce power loss:

Thicker cable



Higher bus voltage

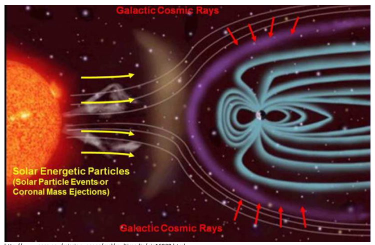


In Order to Reduce power losses and weight, <u>high voltage</u> power supply system will be required

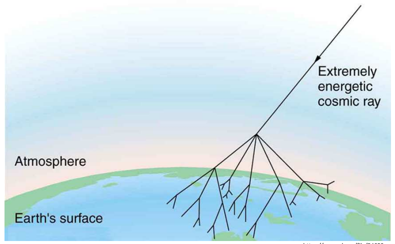
Vision and Goal of the Research

- Contribute to high power devices' <u>reliability in the future space applications</u>
- Develop <u>cosmic ray induced failure rate calculation method</u> for all kind of power devices in various space environments
- Demonstrate that proposed method can give <u>failure rate of the high voltage device at the low earth orbit environment</u>.

Reason of the Failure



http://www.nasa.gov/mission_pages/msl/multimedia/pia16938.html

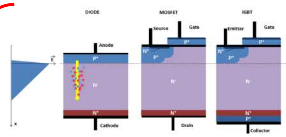


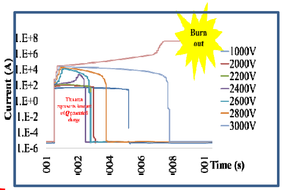
https://voer.edu.vn/file/54639

Space Radiation Effects

Total Dose Effect

Single Event Effect



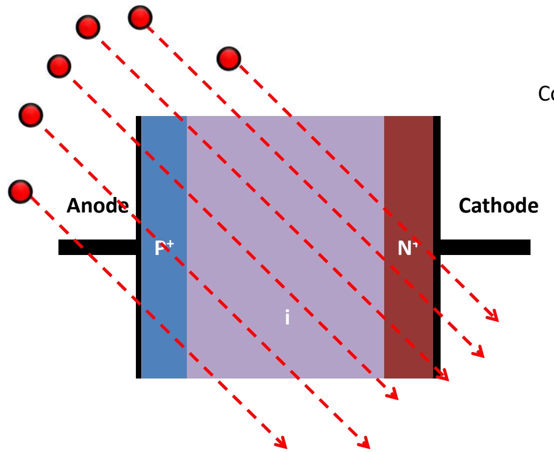


Power Semiconductor Devices Failure occurs inside devices due to high energy particles from space either space or terrestrial.

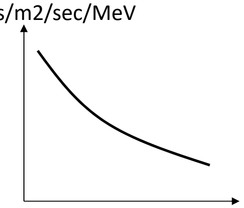
Cosmic Rays induced Single Event Effects in Power Semiconductor Devices *Giovanni Busatto University of Cassino ITALY*

Single Event Failure Phenomena

Space radiation flux

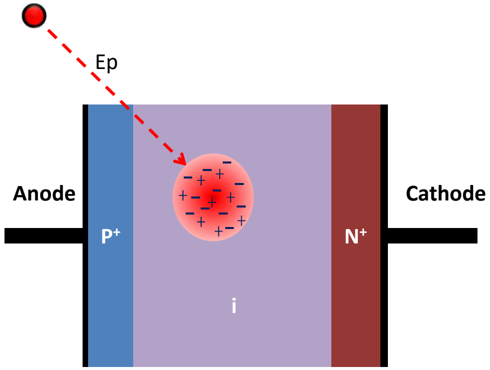


$F(E_p)$

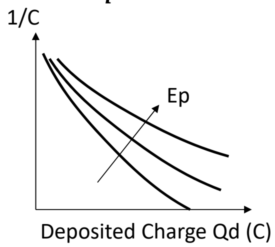


Single Event Failure Phenomena

Charge deposition probability distribution function for 300um silicon with proton energy as a parameter

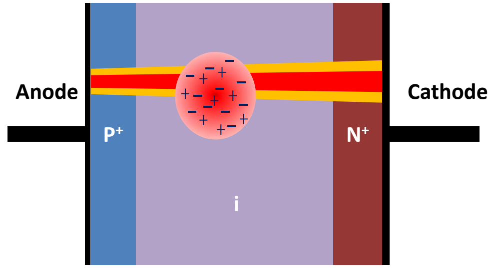


$$\Phi_{E_p}^{300}(Qd)$$

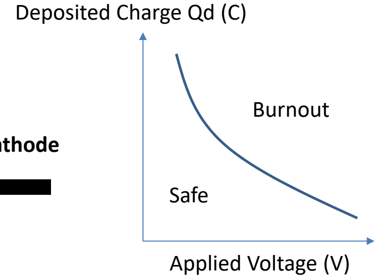


Single Event Failure Phenomena

Burnout Condition based on avalanche phenomena



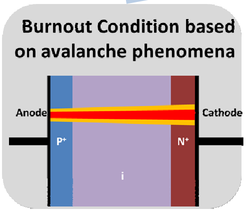
$$Q_{dest}(V)$$



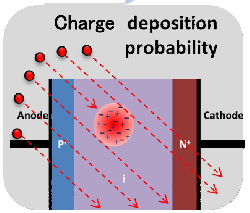
Failure rate calculation formula

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

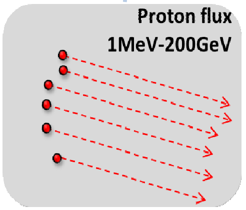
A: chip size



Power Devices Physics
Based on
T-CAD (SYNOPSIS)
SIMULATION



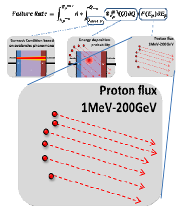
Nuclear Physics
Based on
Study of LITERATURES



Astro Physics
Based on
SPENVIS SIMULATION
Data of LITERATURES

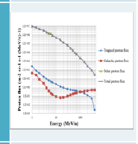
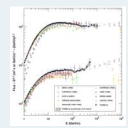
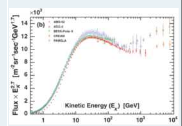
The proposed formula successfully combines the models of the three phenomena
→Detail of each model

Sources of Proton flux data

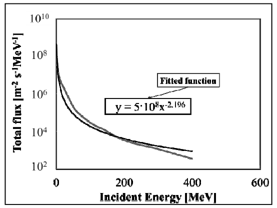


Target is to define $F(E_p)$

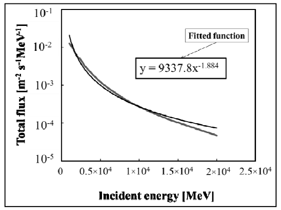
The 90 percent of particles of Cosmic ray are protons in the earth's radiation environment.

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.

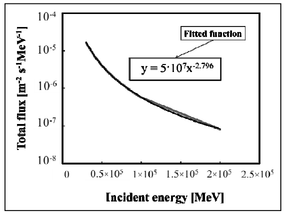
Fitted functions of Proton flux $F(E_p)$



1-400MeV proton flux data at in LEO and its fitted function. /SPENVIS/



1GeV-20GeV proton flux in LEO and its fitted function. /PAMELA/

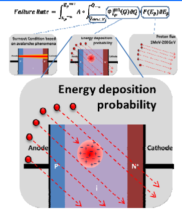


20GeV-200GeV proton flux in LEO and its fitted function. /AMS/

$$F^{Low}(E_p) = 5 \cdot 10^8 \cdot (E_p)^{-2.196} \quad F^{Med}(E_p) = 9337.8 \cdot (E_p)^{-1.884} \quad F^{High}(E_p) = 5 \cdot 10^7 \cdot (E_p)^{-2.796}$$

Proton flux probability is fitted for all the range of energy

Charge deposition Probability



Target is to define $\Phi^{300}_{E_p}(Q)$

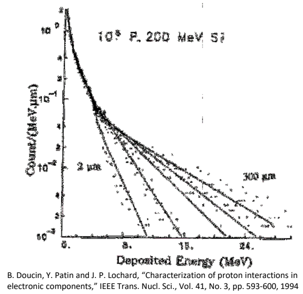
e-h pair generation in Silicon requires energy

E ≈ 3.68 eV/pair

The pair charge is e=1.6*10^-19C

Hence

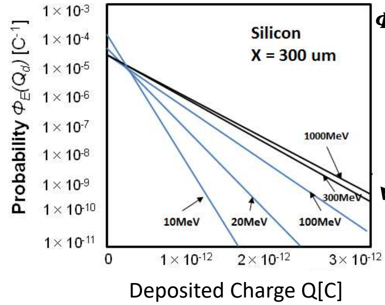
α=2.32*10^13MeV/C



B. Doucin, Y. Patin and J. P. Lochard, "Characterization of proton interactions in electronic components," IEEE Trans. Nucl. Sci., Vol. 41, No. 3, pp. 593-600, 1994

$$\Phi^{x}_{E_p}(E_d) = 10^{b_1{}'(E^x_p)E_d + b_0{}'(E^x_p)}$$

$$E_d = \alpha Q$$

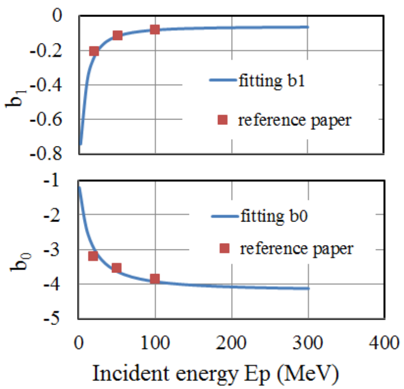


$$\Phi^{300}_{E_p}(Q) = 10^{b_1(E^{300}_p)\alpha Q_g + b_0(E^{300}_p)}$$

E_p [MeV]	b_1	b_0
20	-0.2086	-3.2218
50	-0.1187	-3.542
100	-0.0807	-3.8617

The curve is fitted from the graph using simple parameters

Fitted values for math. expression



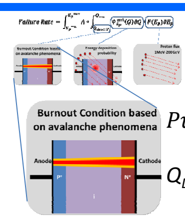
$$b_1(300, E_p) = \frac{-100}{(E_p+15)^{1.8}} - 0.063$$

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

$$\Phi^{300}_{E_p}(Q) = 10^{\frac{-100}{(E_p+15)^{1.8}} - 0.063 + \frac{200}{(E_p+20)^{1.38}} - 4.2}$$

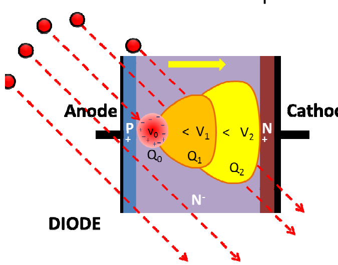
Fitted function is expanded to higher energy level

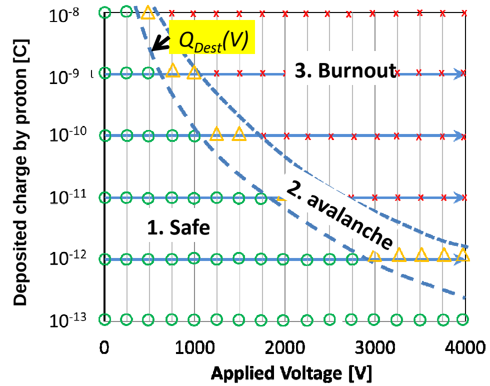
Charge Avalanche Multiplication in Device



Purpose is to define $Q_{Dest}(V)$ by

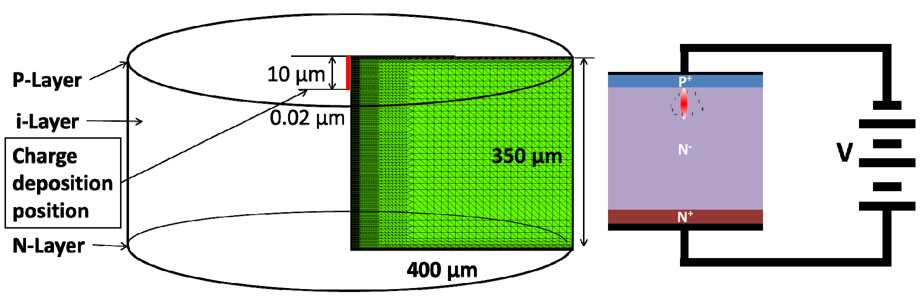
Avalanche Multiplication





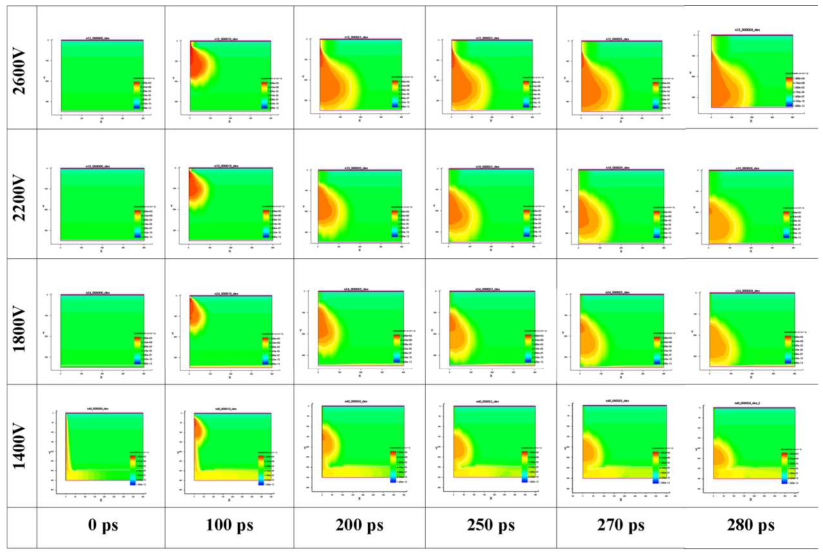
- **Combination of charge and voltage need to be defined**
- **Each point require transient TCAD simulation for Avalanche**
- **More than 100 points needed to be simulated**
- **➔Problem of simulation time**

Simulation Consideration



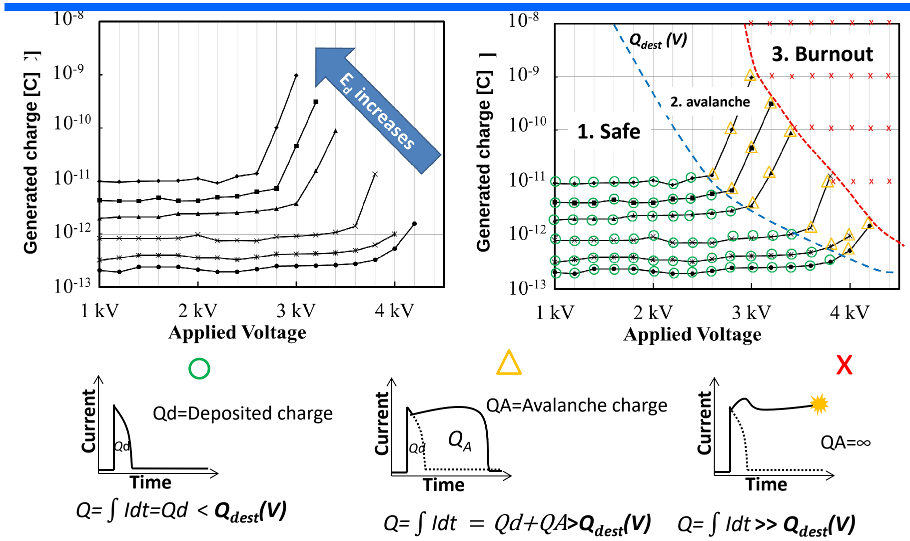
Homogenous structure of diode makes it to be able to perform Cylindrical Simulations (Quasi-3D) instead of ordinary 3D simulation. =>reduction of simulation time

Electron current density distribution by voltage



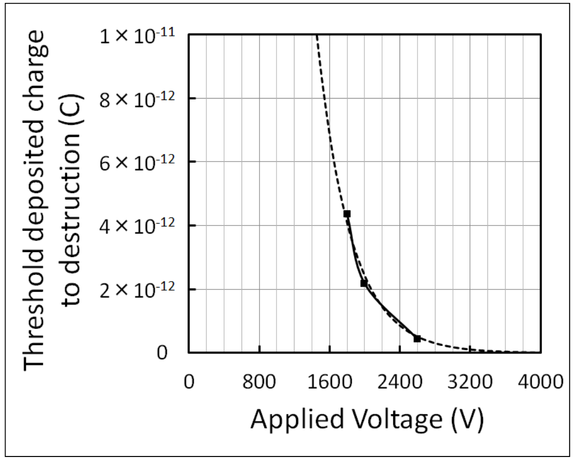
The charge generation increases when applied voltage increases

Device destruction curve due to charge



The safe area's border defines destruction charge curve

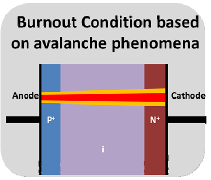
Destruction Charge Function



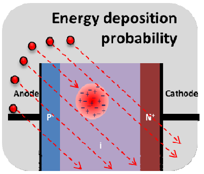
$$Q_{dest}(V) = 7 * 10^{-10} e^{-0.003V}$$

Destruction charge function $Q_{dest}(V)$ defined by fitting simulation result

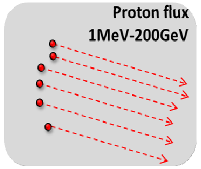
Failure rate calculation



$Q_{dest}(V) = 7 * 10^{-10} e^{-0.003V}$



$\Phi_{E_p}^{300}(Q) = 10^{\frac{-100}{(E_p+15)^{1.8}} - 0.063 + \frac{200}{(E_p+20)^{1.38}} - 4.2}$



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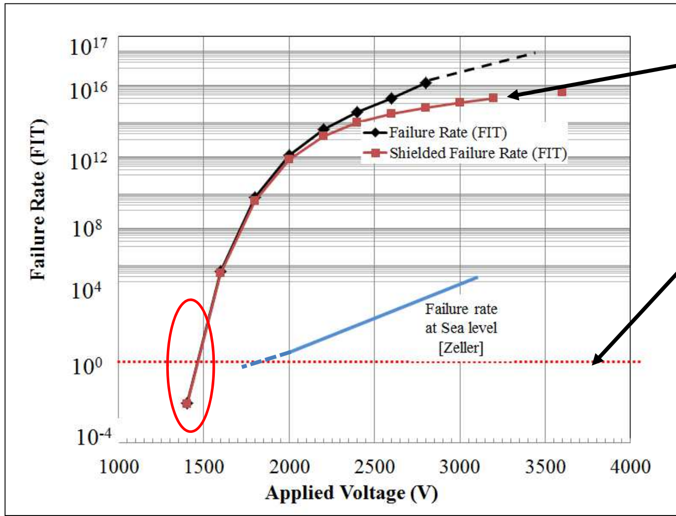
$F^{High}(E_p) = 5 \cdot 10^7 \cdot (E_p)^{-2.796}$

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

By combining three models we can calculate failure rate under space radiation environments

Calculated Failure rate of 3.3kVdiode in Space

3.3kV PiN diode, Proton incident energy range 1MeV-200GeV



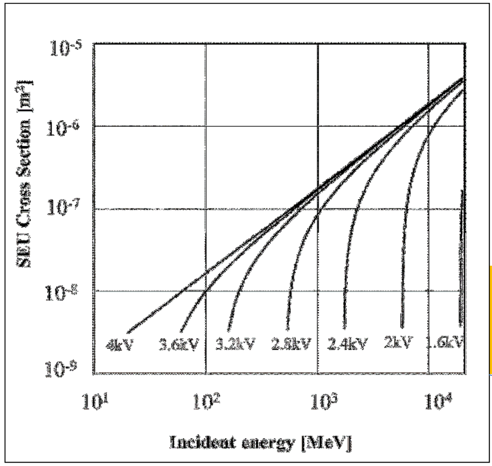
Aluminum shield affects only low energy range

Confirmed failure rate for power device[1 FIT]

De-rating Value

Sea level <1800V-DC line voltage ⟹ Space App <1400V DC-line voltage

Voltage Dependent SEB Cross Section



The **SEB cross section** for high voltage power semiconductor device depends on applied voltage (3.3kV PiN diode, 1MeV-20GeV)

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

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

The SEB cross section of device can be used for any radiation environment failure rate calculation

Conclusion

- Cosmic ray induced failure rate calculation method for all kind of power devices in various space environments is proposed
- It is demonstrated that proposed method can give failure rate of the high voltage device at the low earth orbit environment
- The new method will contribute to high power devices' reliability in the future space applications