Neutron-Induced Soft Error Analysis in MOSFETs from a 65nm to a 25 nm Design Rule using Multi-Scale Monte Carlo Simulation Method

Shin-ichiro Abe[1], Yukinobu Watanabe[1], Nozomi Shibano[2], Nobuyuki Sano[2], Hiroshi Furuta[3], Masafumi Tsutsui[3], Taiki Uemura[3], and Takahiko Arakawa[3]

(e-mail: abe@aees.kyushu-u.ac.jp)

1. Departments of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan

2. Institute of Applied Physics, University of Tsukuba, Ibaraki 305-8571, Japan

3. Semiconductor Technology Academic Research Center, STARC, Kanagawa 222-0033, Japan

Purpose

- To perform SER analyses and compare with the scaling trend
- To investigate the impact of secondary ions on soft errors
- To clarify the incident energy range in which terrestrial neutrons have significant influence on soft errors

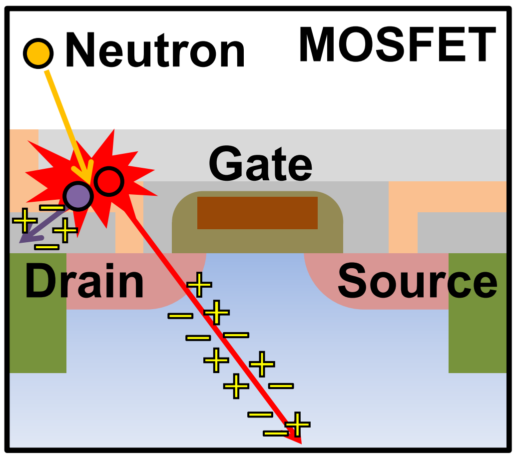
Abstract

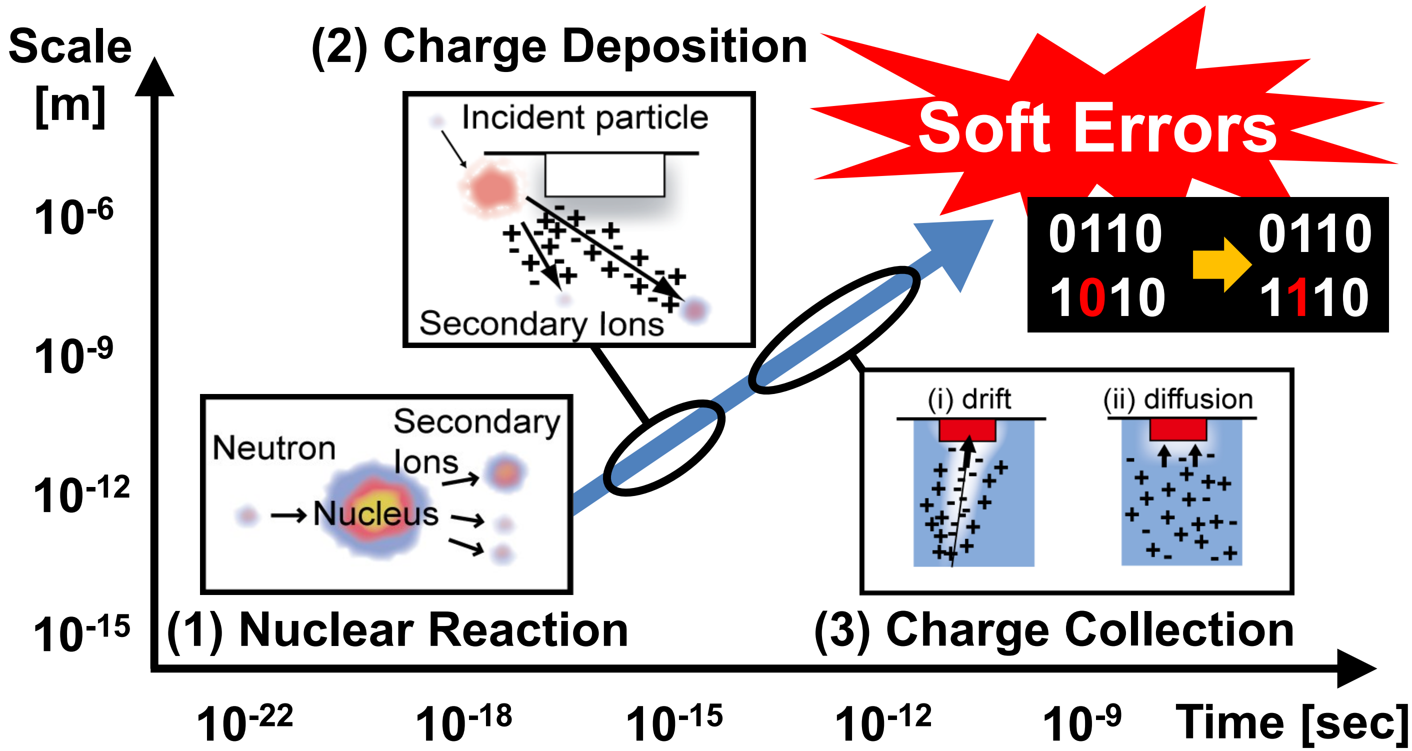
We have analyzed terrestrial neutron-induced soft errors in MOSFETs from a 65 nm to a 25 nm design rule by means of multi-scale Monte Carlo simulation using PHITS-HyENEXSS code system. The resulting scaling trend of SERs per bit is still decreasing similar to other predictions. From this analysis, it is clarified that secondary He and H ions provide a major impact on soft errors with decreasing critical charge. It is also found that terrestrial neutrons with energies up to several hundreds of MeV have a significant contribution to soft errors regardless of design rule and critical charge.

Background

Soft Error: Temporary malfunction of microelectronic devices.

They are mainly due to terrestrial cosmic-ray neutrons on the ground.





To simulate the soft error rate with high reliability, it is required …

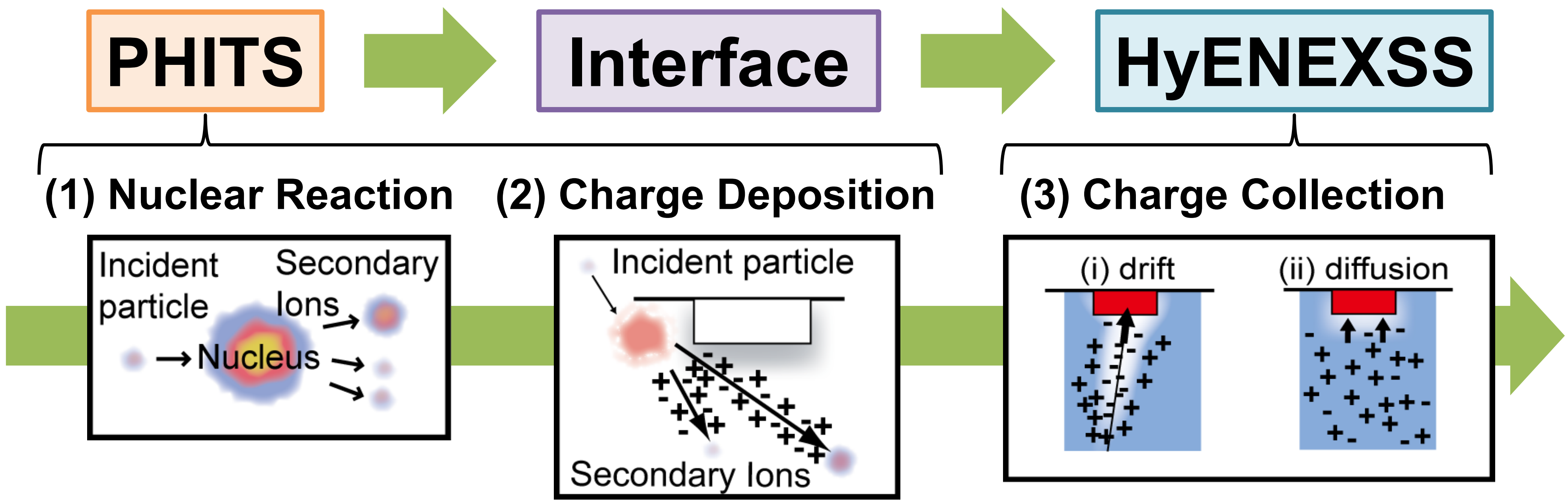
- **to employ highly reliable physical models.**
- **to synthesize each physical model at the difference stages.**

Our previous work

Ref.) S.Abe et.al., IEEE Trans. on Nucl. Sci., vol.59, no.4, pp.965-970, 2012.

We have developed a multi-scale Monte Carlo simulation code system by linking PHITS and HyENEXSS.

This code system enables integrated simulation from nuclear reaction to charge collection



PHITS (Particle and Heavy Ion Transport code System)

Ref.) K. Niita, et.al., PHITS: Particle and Heavy Ion Transport code System, Version 2.23, JAEA-Data/code 2010-022 2010.

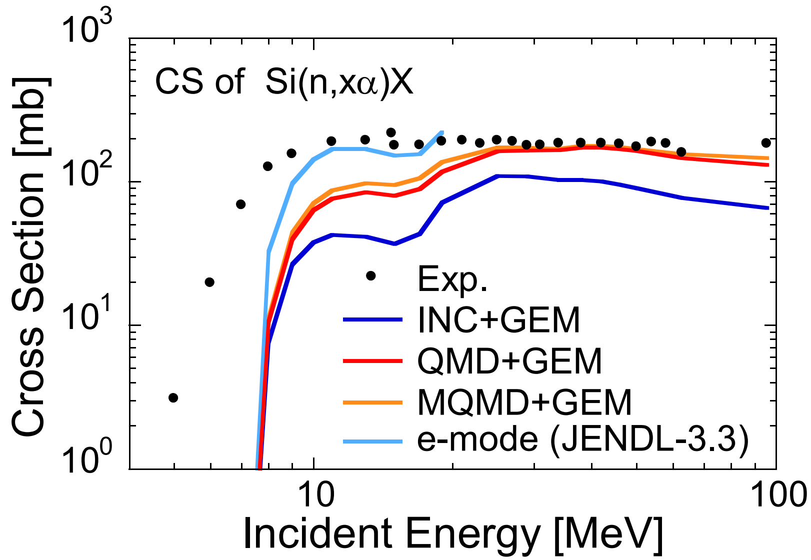
3-D Mote Carlo simulation code to calculate
Nuclear Reaction and Transport of particles and heavy ions

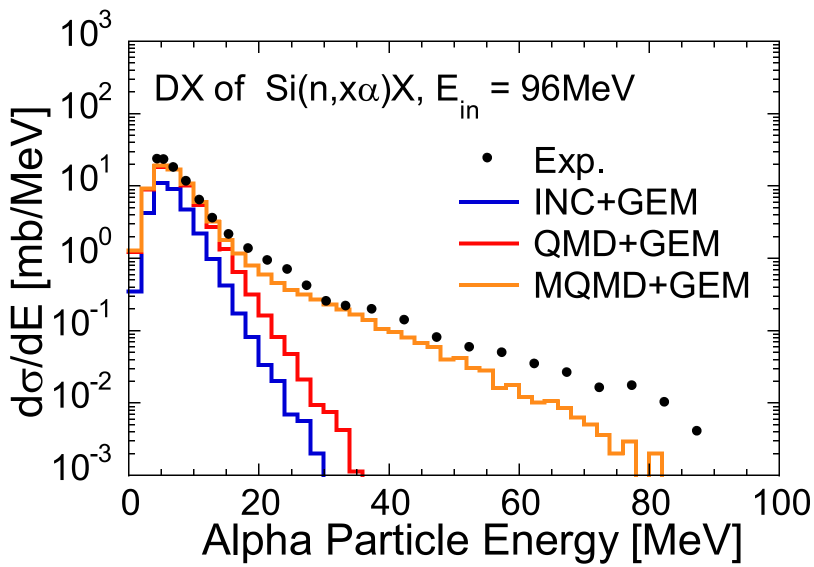
✓ **Nuclear reaction model contained in the PHITS code**

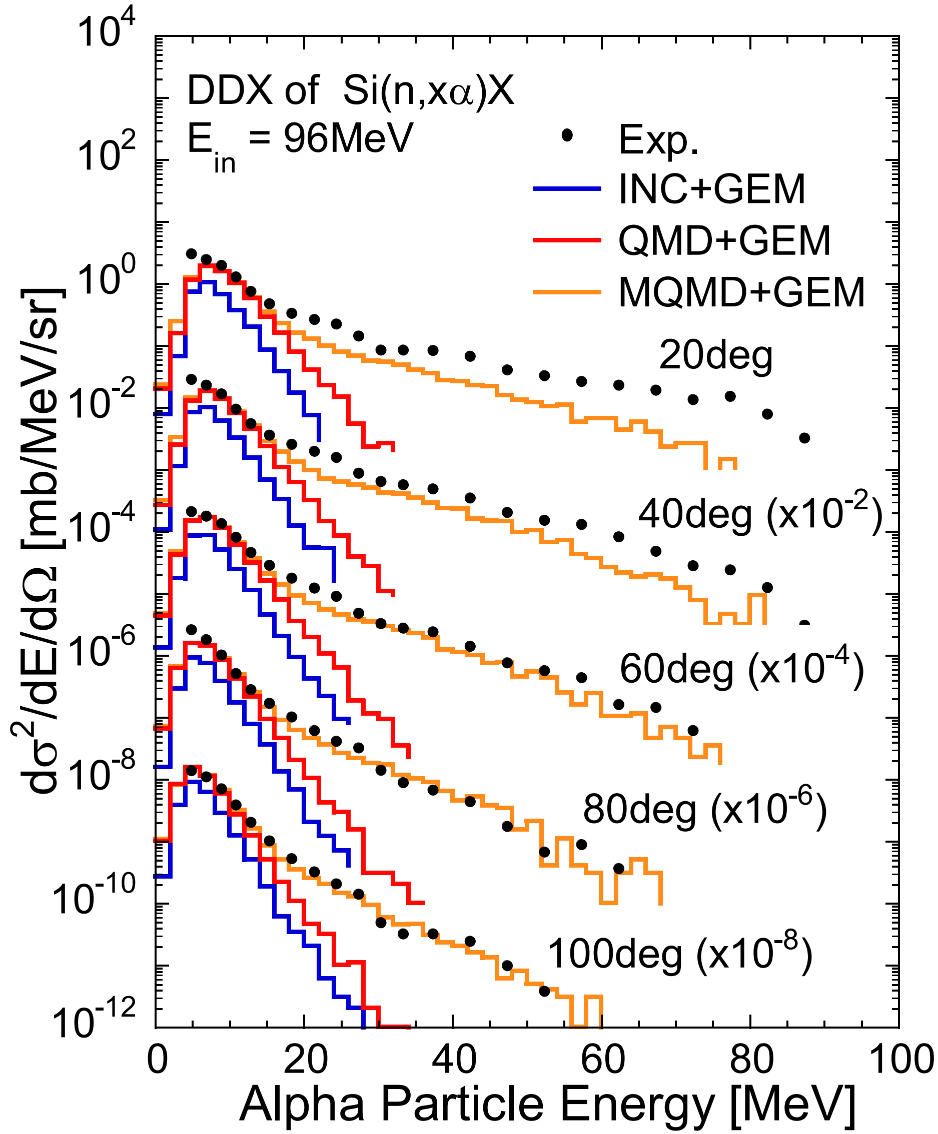
Dynamic Process	Intra Nuclear Cascade (INC) model Quantum Molecular Dynamics (QMD) mode etc…
Evaporation Process	Statistical Decay Model (SDM) Generalized Evaporation Model (GEM) etc…
Neutron-induced reaction below 20 MeV	“event generator mode (e-mode)” with evaluate nuclear data library

Information: Accuracy of nuclear reaction model

Ref. of Comparisons) S. Abe *et.al.*, Proc. of Int. Nucl. Phys. Conf. 2010. etc…
Ref. of MQMD) Y. Watanabe and D. N. Kadrev, EDP Science, pp. 1121-1124, 2008.

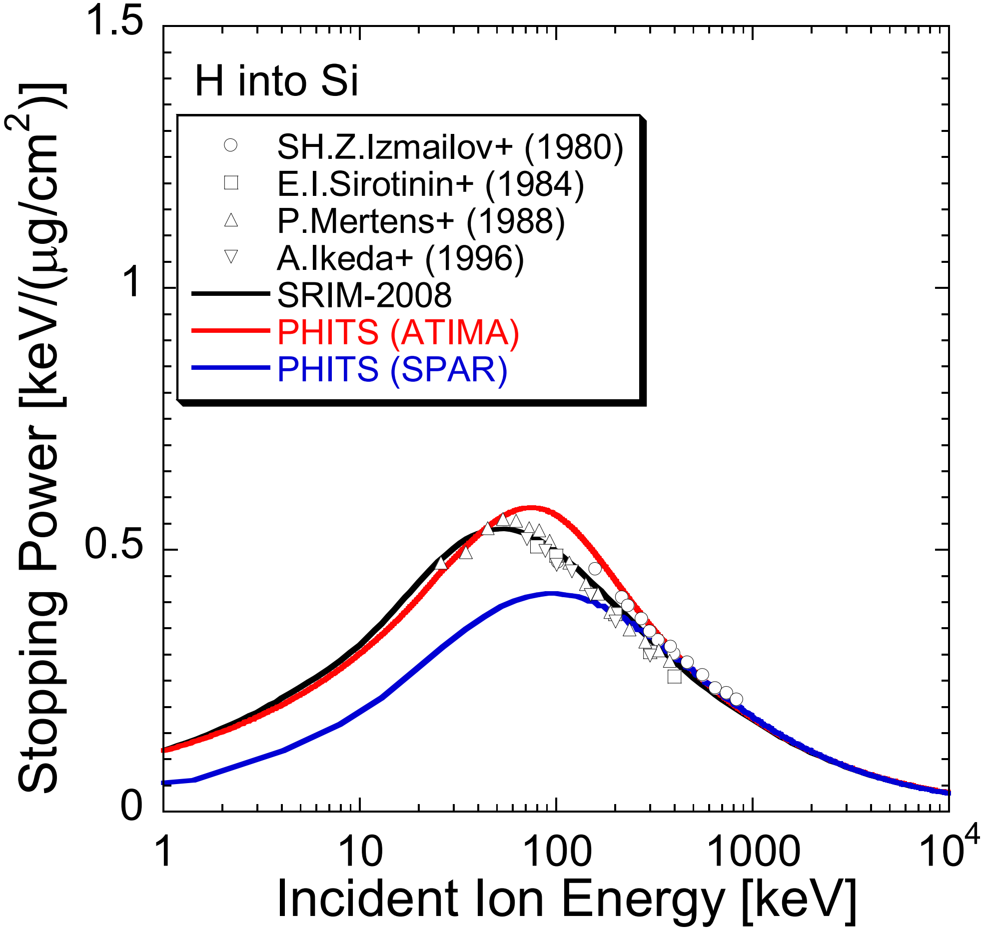


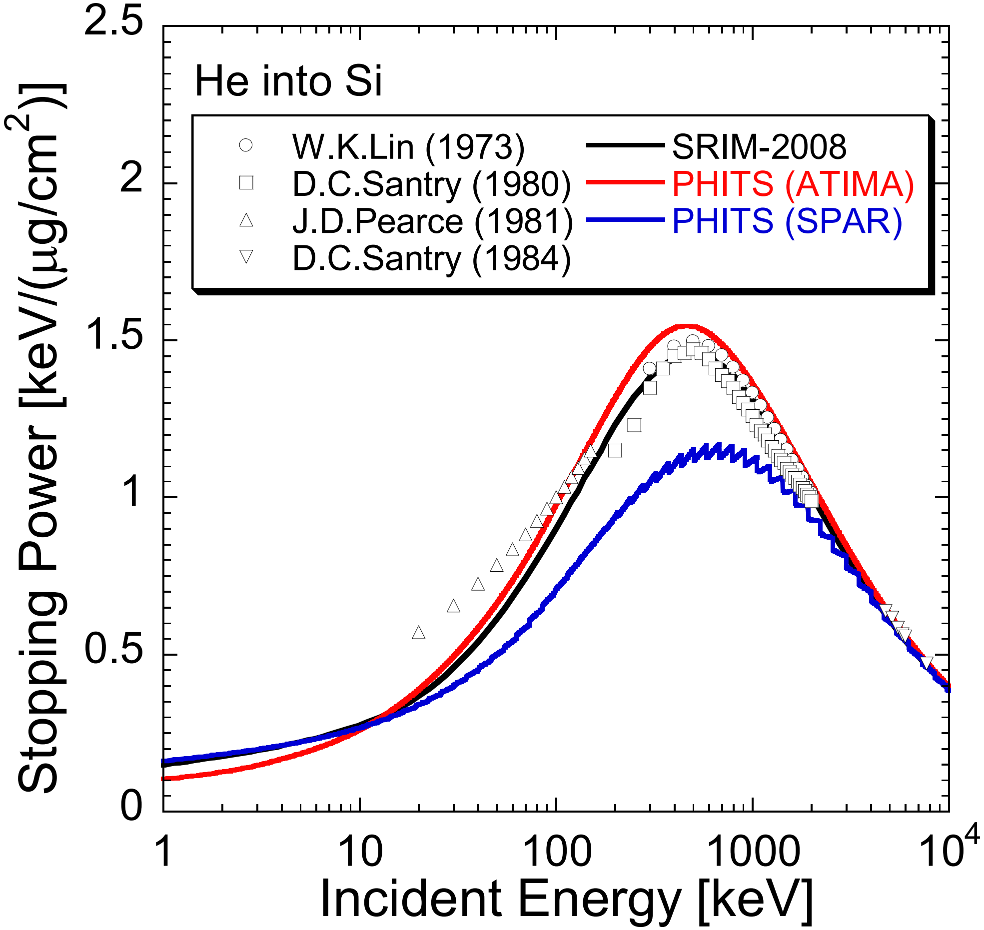




Information: Accuracy of stopping power calc.

Ref.) S. Abe, Thesis for master's degree, Department of Advanced Energy Engineering Sciences, Kyushu University, Japan, 2010. (in Japanese)





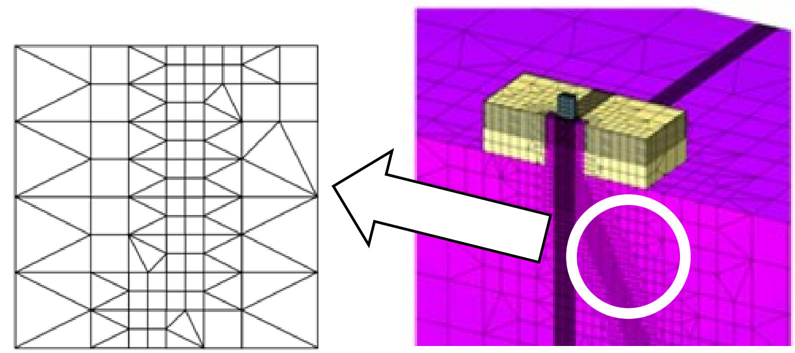
Interface tool "takomesh"

Ref.) N. Shibano, Thesis for master's degree, Institute of Applied Physics, University of Tsukuba, Japan, 2010. (in Japanese)

Secondary ions are emitted at arbitrary directions. → **"takomesh" generate the mesh structure optimized for soft error simulation.**

□ Octree mesh method

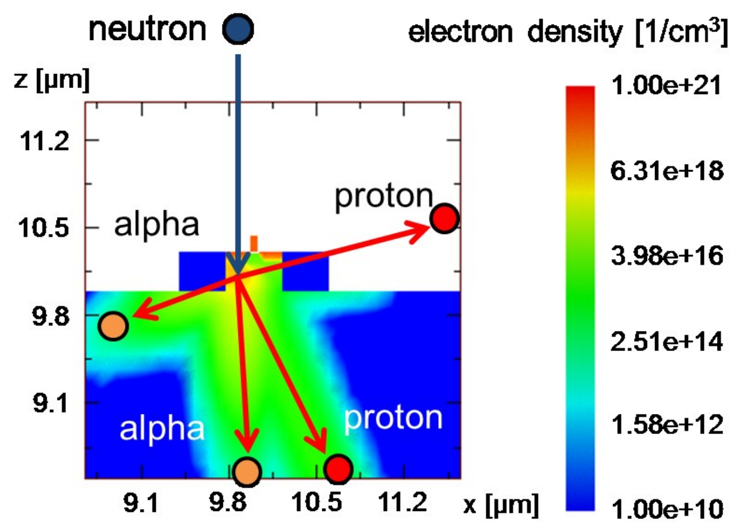
Subdivide rectangular parallelepiped shaped mesh into 8 small meshes recursively.



e.g.) Spallation reaction of

$$n + {}^{28}Si \rightarrow {}^{16}O + 2\alpha + 2p + 3n$$

The initial charge distribution is generated normally even though many secondary ions were passed.

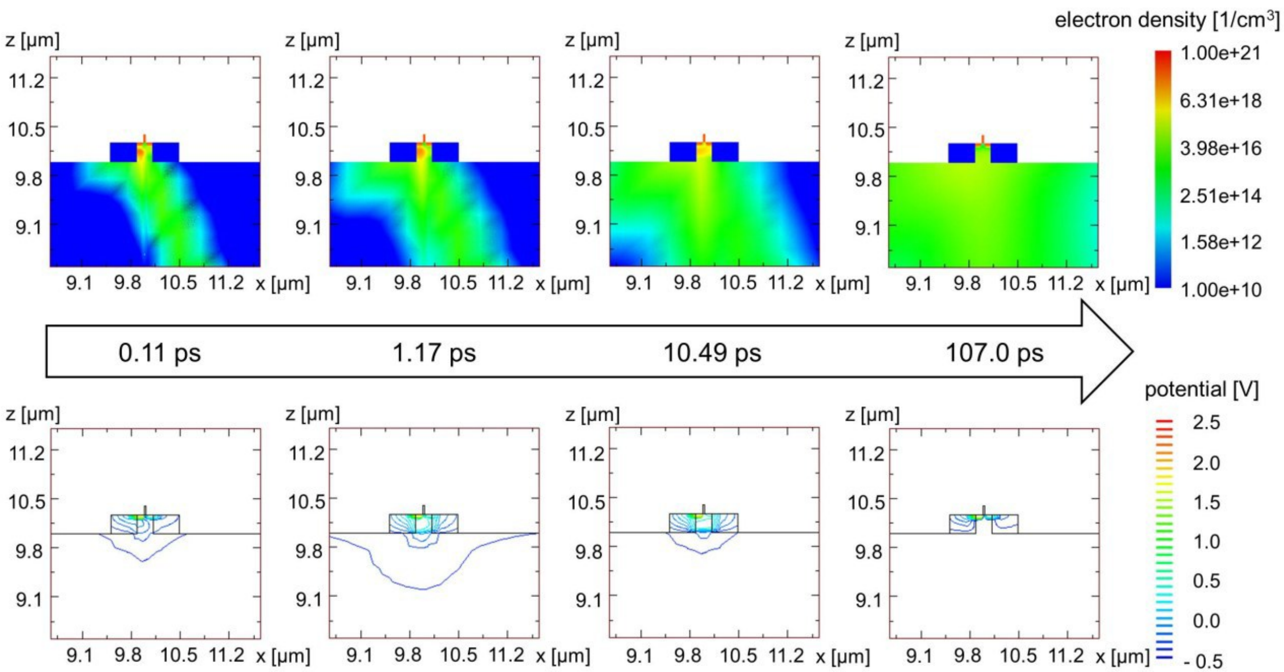


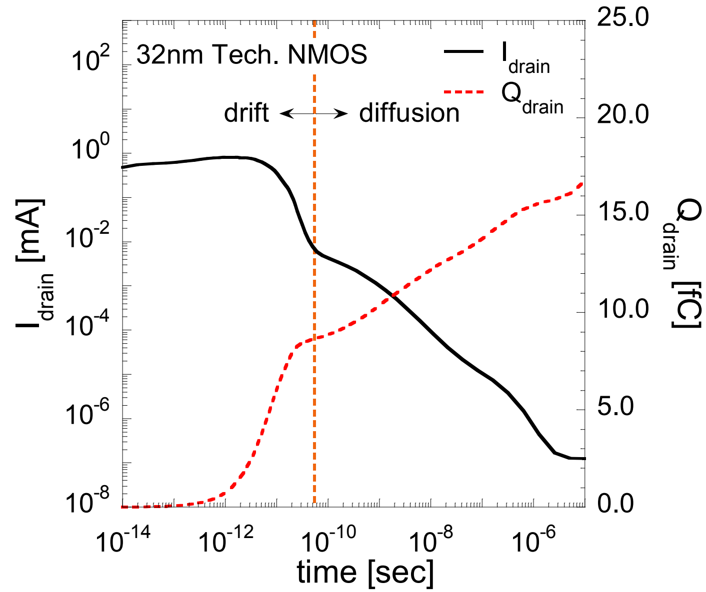
HyENEXSS (Hyper Environment etc…)

Ref.) 3-D TCAD simulator HyENEXSS, developed by Selete: Semiconductor Leading Edge Technologies Inc.; http://www.selete.co.jp

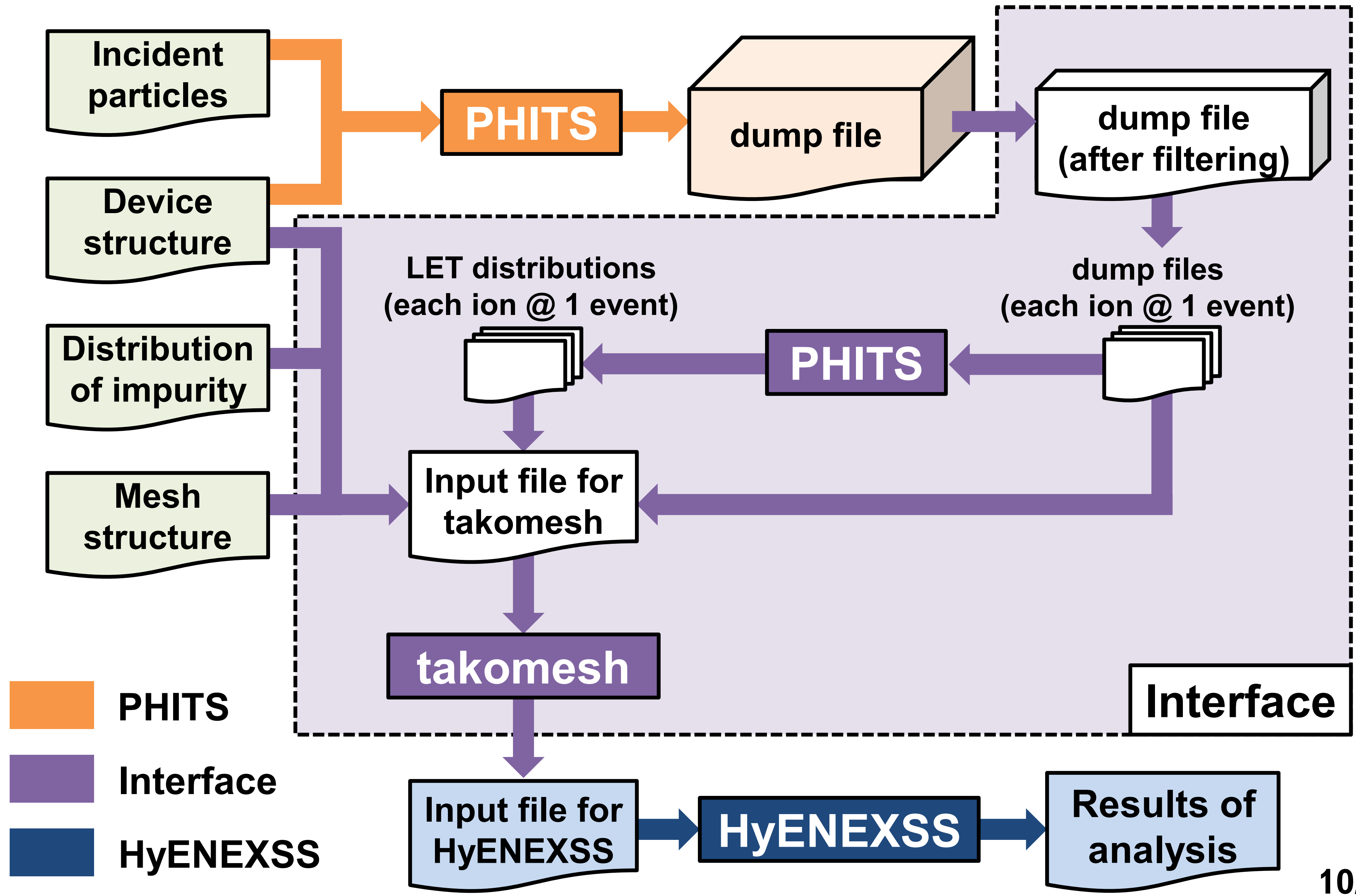
3-D TCAD simulator that consisting of Process Simulator and Device Simulator

Transient analysis is performed by Drift-Diffusion method.





Simplified flowchart of SER analysis



How to calculate SER

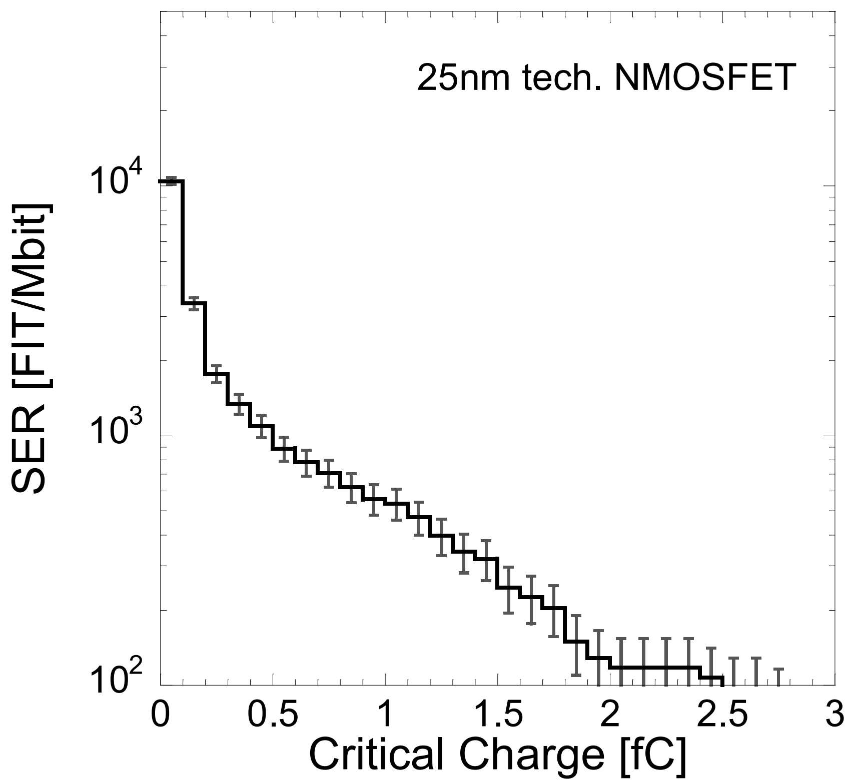
$$SER(Q_c) = \frac{F \times A}{N_{in} \times N_{bit}} \int_{Q_c}^{\infty} N(q)dq$$

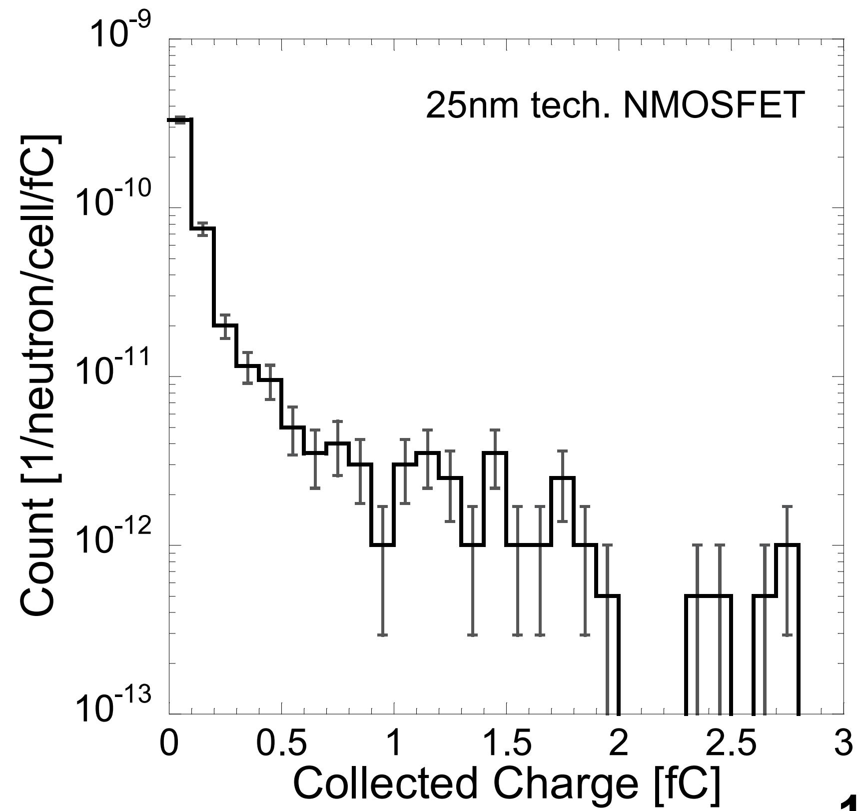
F **: total neutron flux [cm^{-2}s^{-1}]**

A **: surface area of device [cm^{2}]**

N_{in} **: number of incident neutrons in PHITS calculation**

N_{bit} **: number of bit cells**





Structure and parameter of NMOSFETs

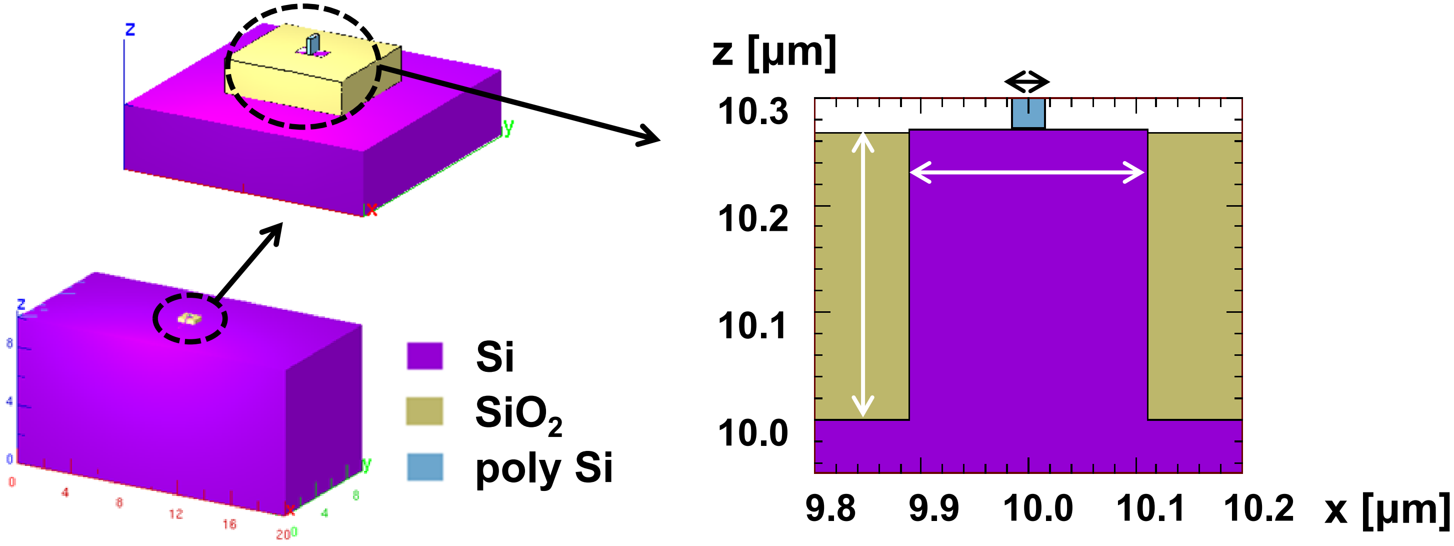
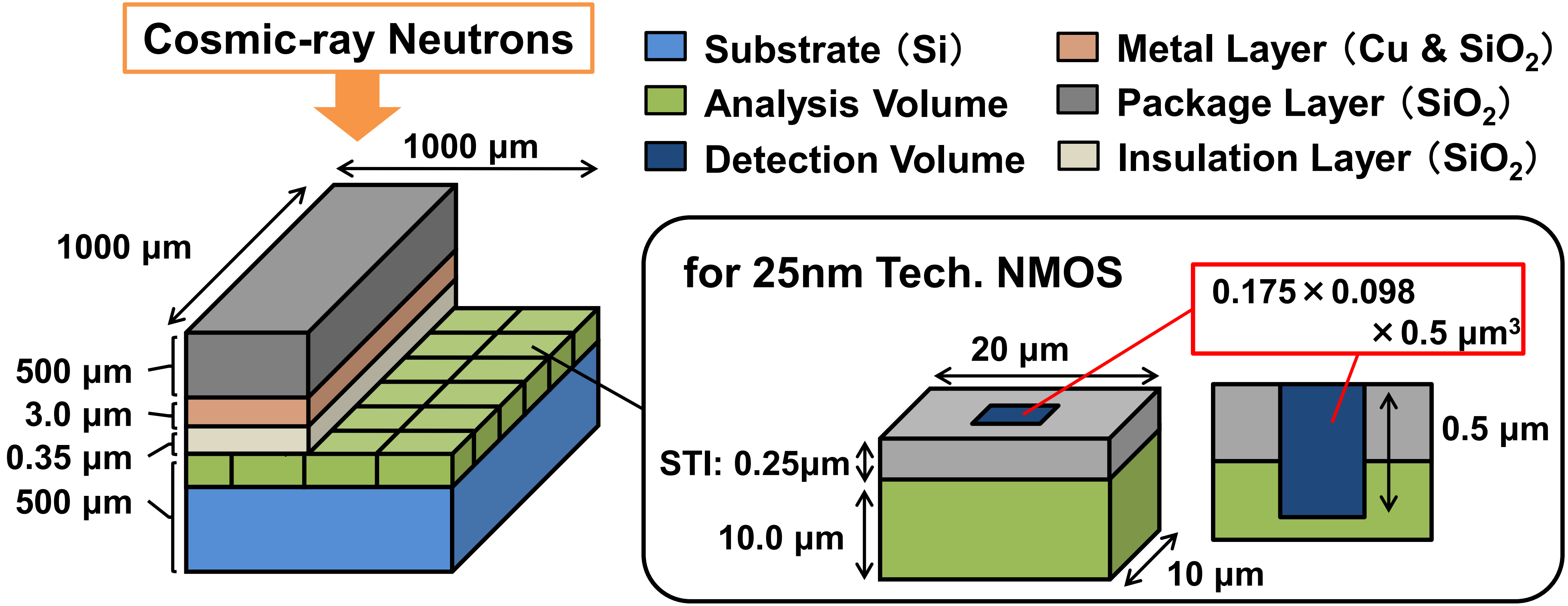


TABLE 1: PARAMETER OF NMOSFET FOR EACH TECHNOLOGY

Technology [nm]	65	45	32	25
Critical Charge [fC]	2.0	1.5	0.95	0.6
Bias voltage of drain [V]	1.2	1.1	1.0	0.9
Gate oxide thickness [nm]	2.2	2.0	1.7	1.5
Active area length [μm]	0.455	0.315	0.224	0.175
Active area width [μm]	0.248	0.172	0.12	0.098
STI depth [μm]	0.31	0.29	0.27	0.25

Test device structure to make dump file



The event was detected when secondary ions pass through Analysis Volume, or generated in the Analysis Volume.

The number of incident neutrons: 4,000,000,000

➡ The number of detected events: 3,800,000

It is necessary to select the analyzed events.

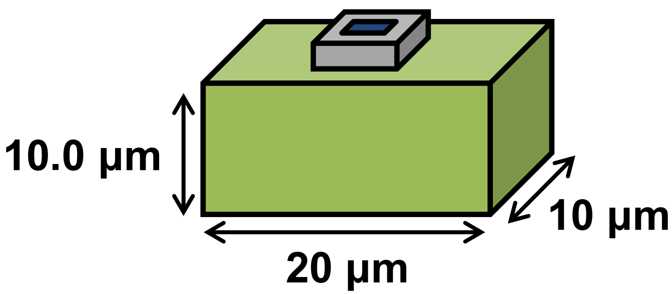
How to choose event

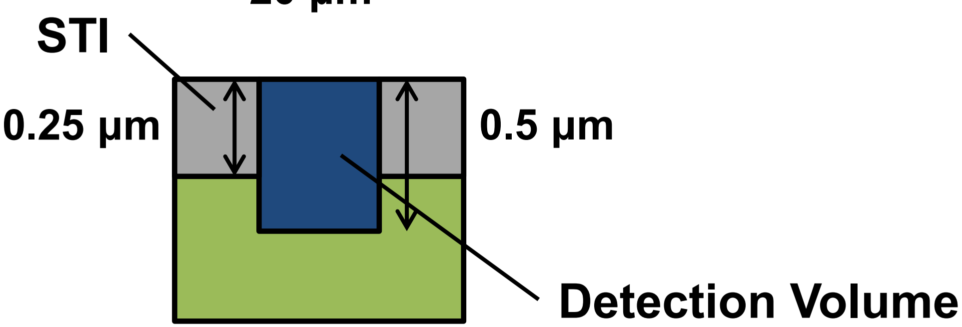
= Condition of Event Selection =

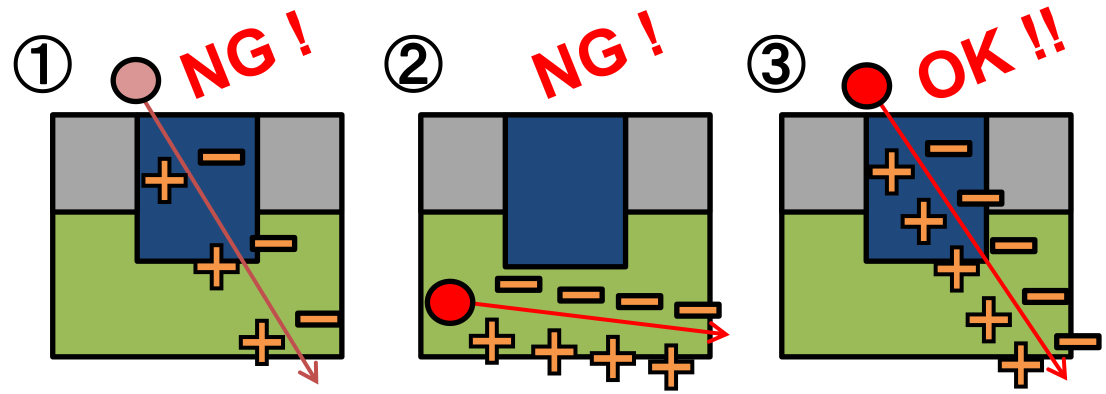
① If the carge deposited in the analysis volume is less than critical charge, the event is rejected.

② If any secondary ions do not pass through the detection volume, the event is also rejected.

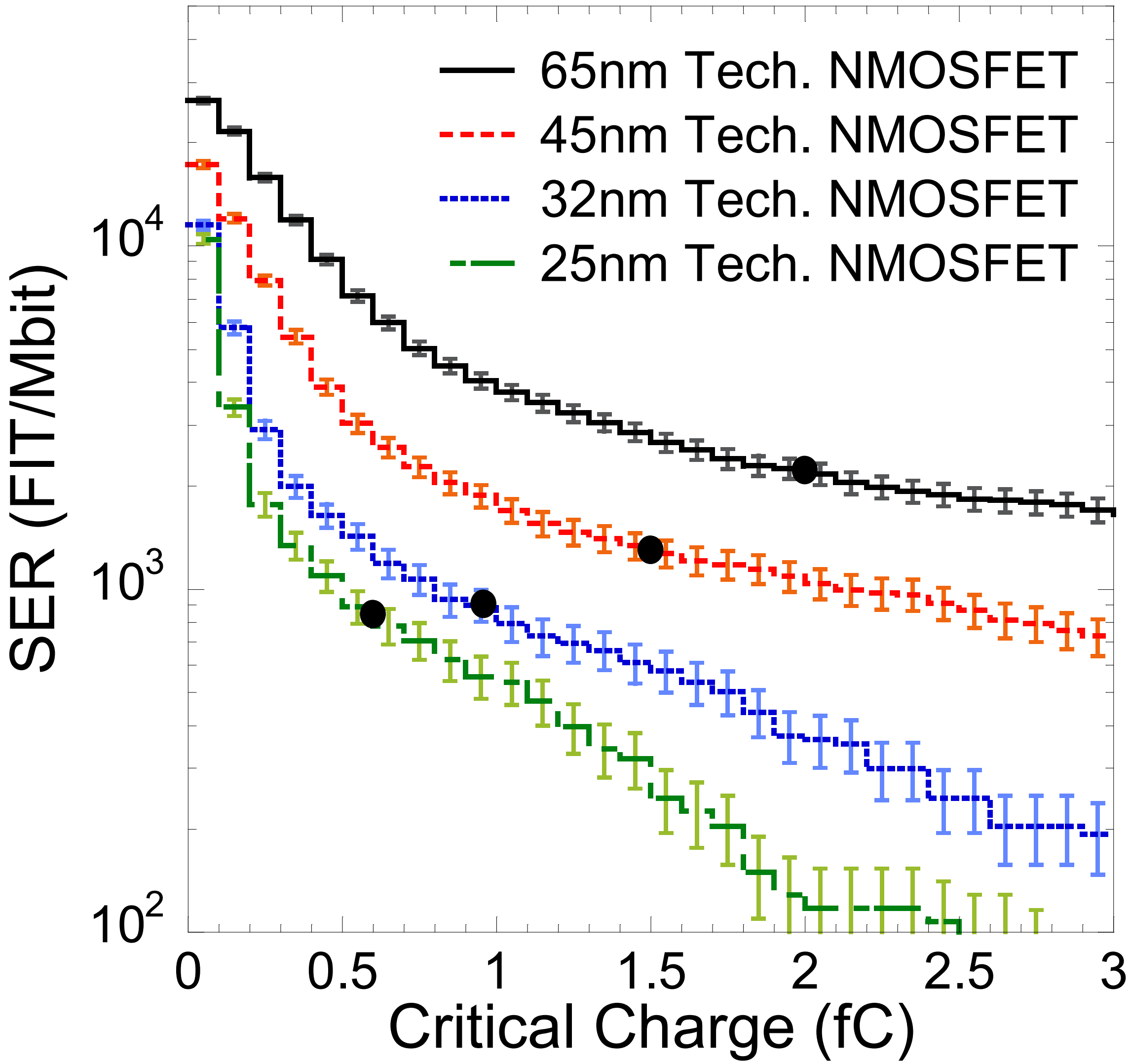
Analysis Volume





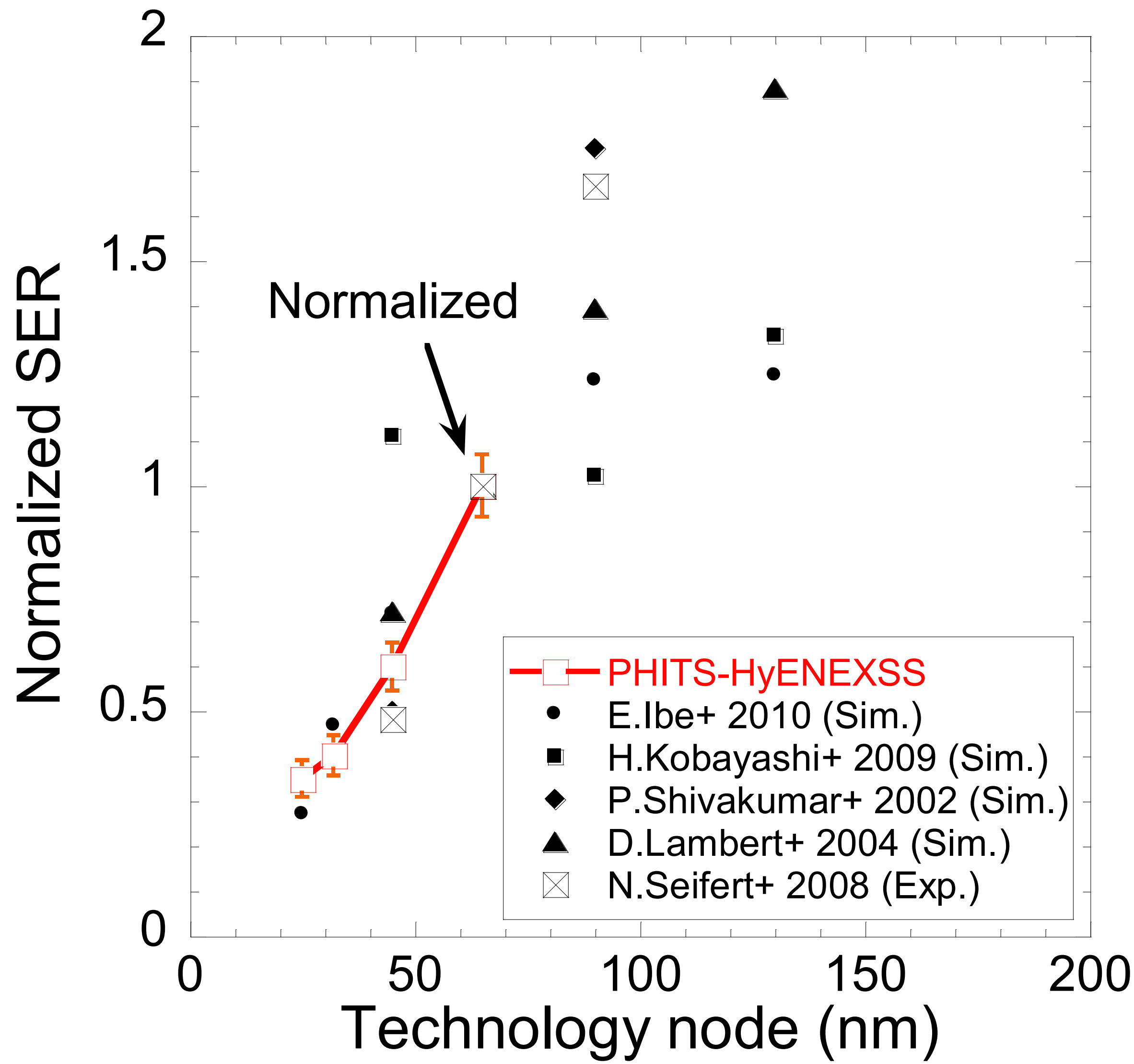


Results of SER analyses



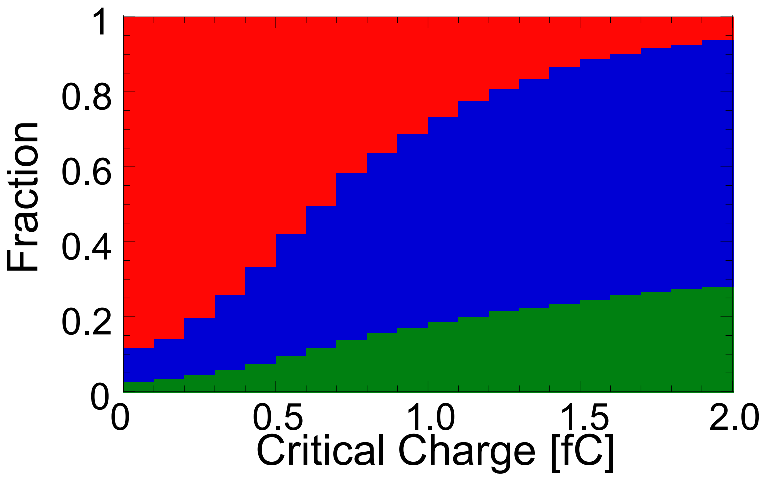
✓ **The calculated SERs per bit have a decreasing trend as the device technology scales down.**

Scaling trend of SER

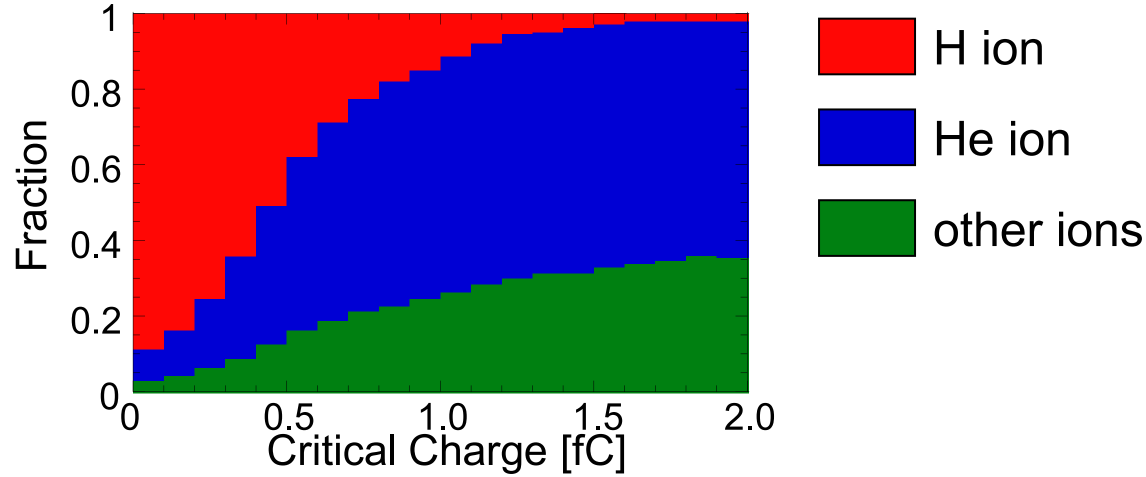


✓ **The present result shows a decreasing trend similar to other SER predictions.**

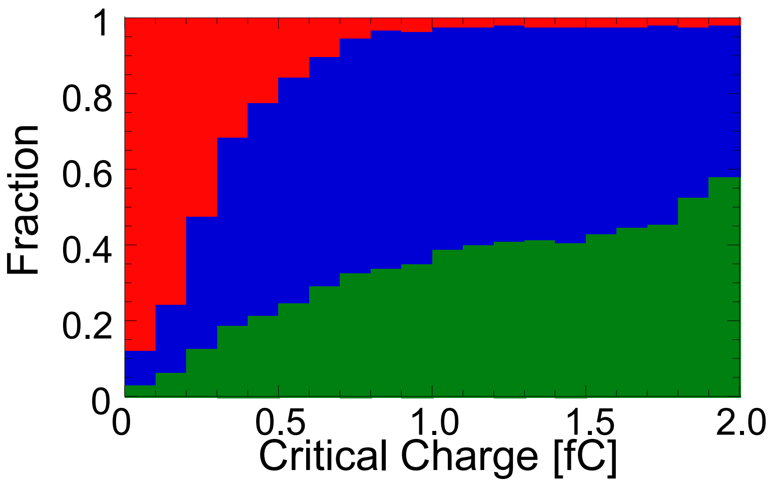
Impact of secondary ion species on SER



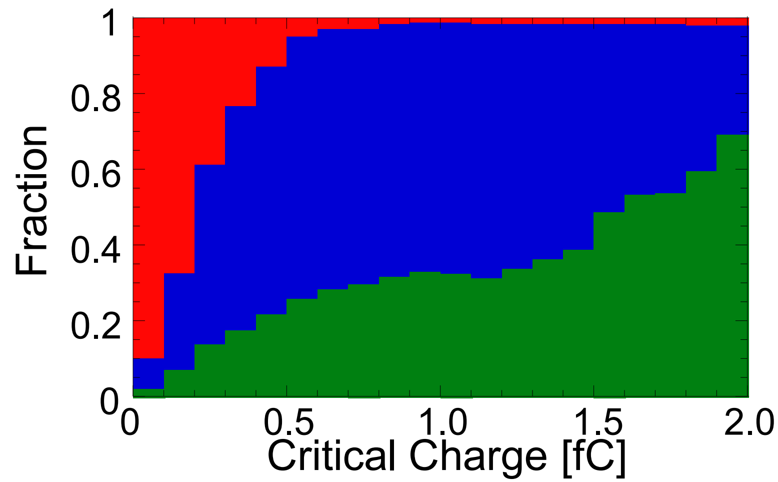
(a) 65nm Tech. NMOSFET（Q_c = 2.0fC）



(b) 45nm Tech. NMOSFET（Q_c = 1.5fC）



(c) 32nm Tech. NMOSFET（Q_c = 0.95fC）

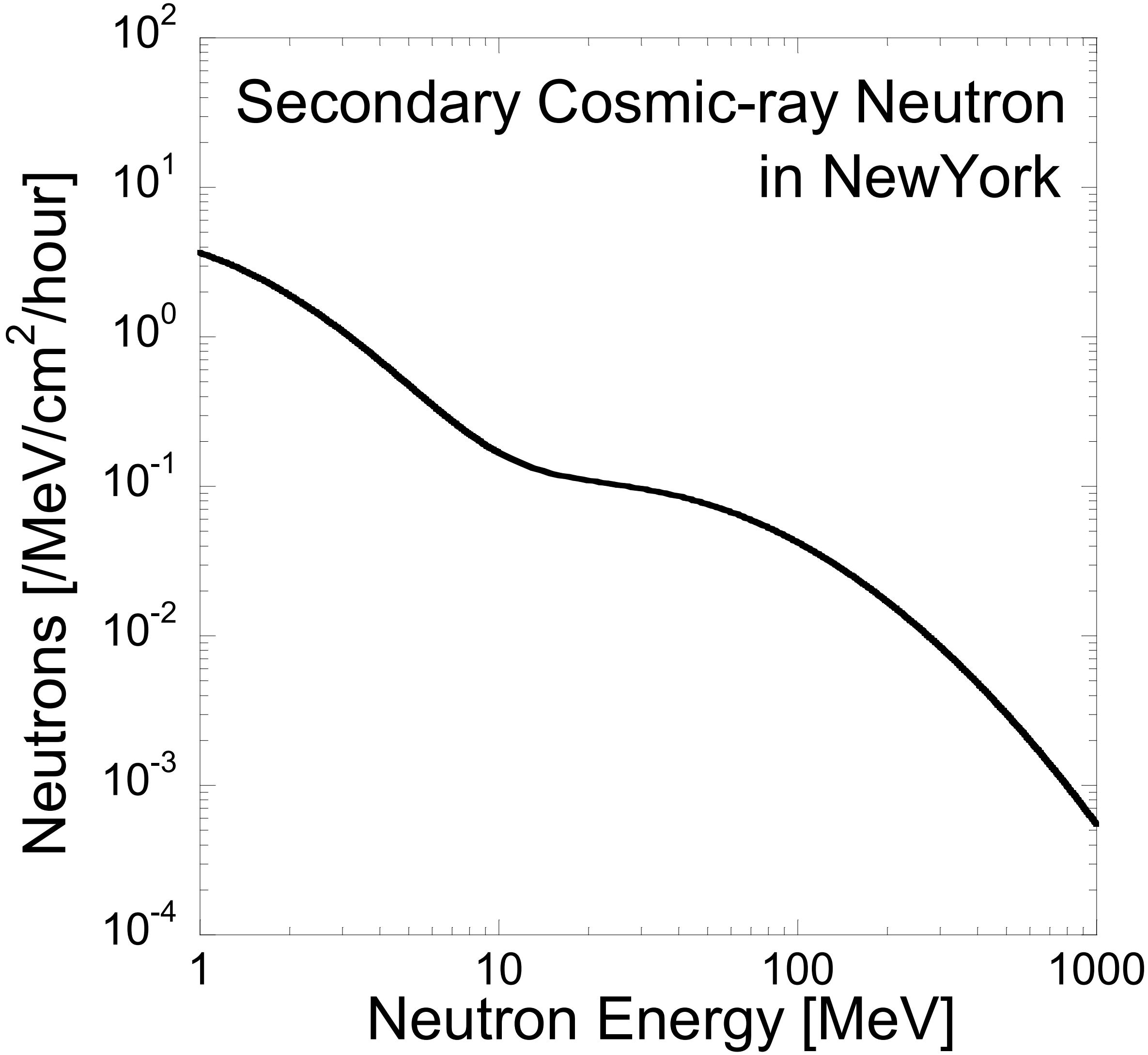


(d) 25nm Tech. NMOSFET（Q_c = 0.6fC）

- ✓ **He ions have a major cause of soft errors.**
- ✓ **H ions impact SER significantly when Q_c is reduced.**

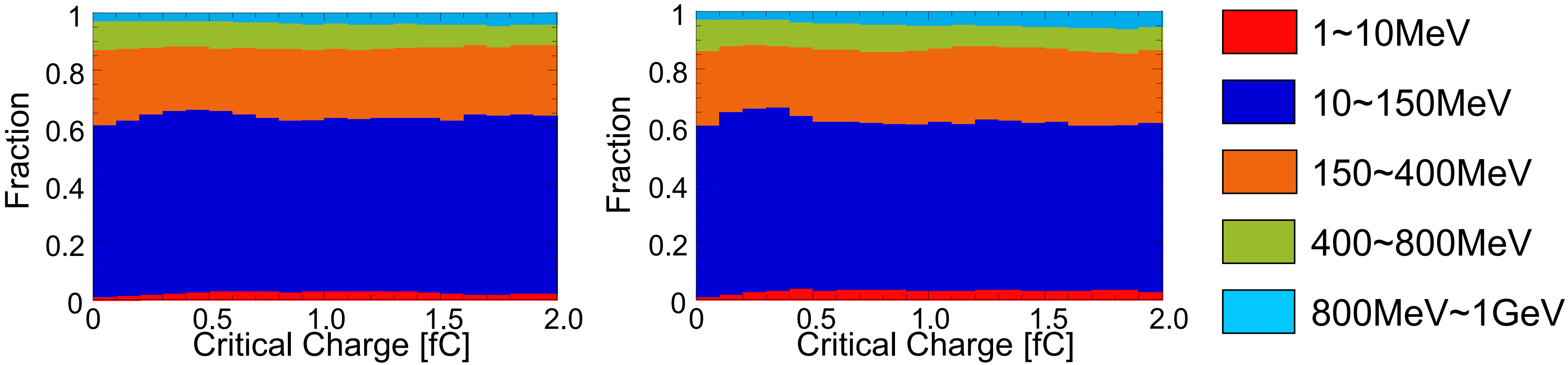
Information: Cosmic-ray neutron spectrum

Ref.) JEDEC Standard JESD89A, Oct. 2006.; http://www.jedec.org

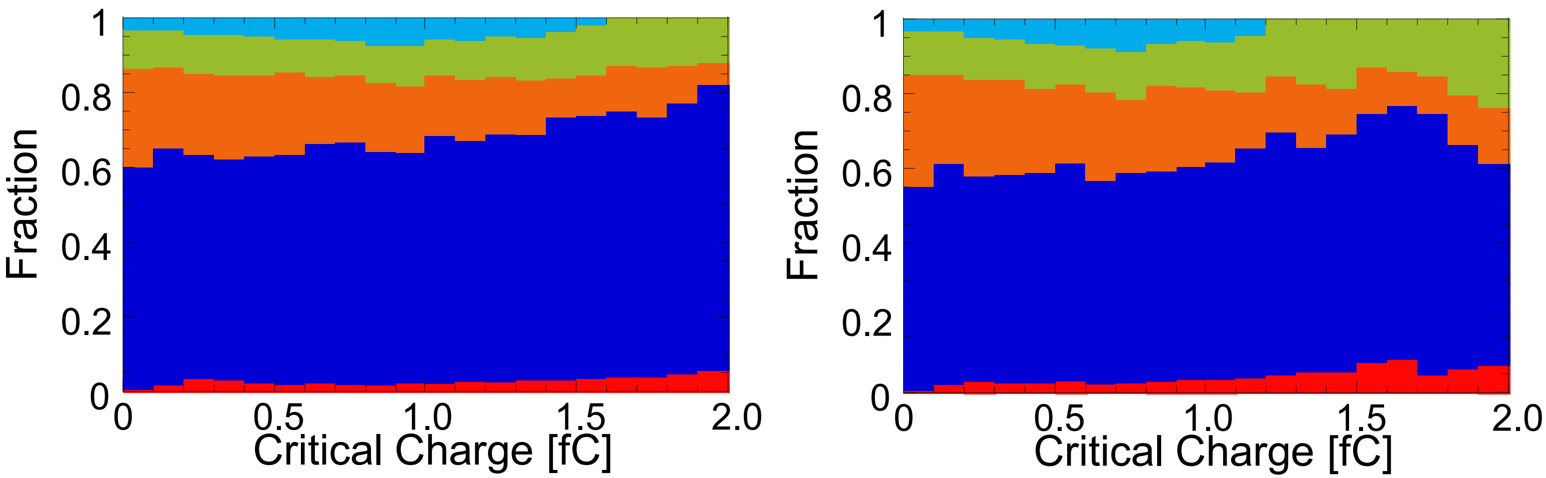


Energy Range	fraction
1~10MeV	0.355
10~150MeV	0.411
150~400MeV	0.149
400~800MeV	0.047
800MeV~1GeV	0.007

Dependence of SER on incident neutron energy



(a) 65nm Tech. NMOSFET（Q_c = 2.0fC） **(b) 45nm Tech. NMOSFET（Q_c = 1.5fC）**



(c) 32nm Tech. NMOSFET（Q_c = 0.95fC） **(d) 25nm Tech. NMOSFET（Q_c = 0.6fC）**

- ✓ **The contribution of neutrons below 10MeV is a few percent.**
- ✓ **Incident neutrons up to 400MeV account for about 80%.**

Conclusion

- ✓ The results show that the scaling trend of SERs per bit is still decreasing similar to the other predictions.
- ✓ He ions have a major cause of soft errors, and H ions impact soft errors considerably if the critical charge is further reduced.
- ✓ About 80% of terrestrial neutron-induced soft errors can be caused by neutrons up to 400 MeV.

Accurate estimation of production of H and He ions in the neutron energy range up to several hundreds of MeV plays a key role in terrestrial neutron-induced soft error simulation.

Acknowledgement

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