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shaping tomorrow with you

ソフトエラー評価・対策技術

富士通セミコンダクター

今日のお話の詳細は以下

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SISPAD 2014

- T. Kato, T. Uemura, H. Matsuyama, "High-Accuracy Estimation of Soft Error Rate using PHYSERD with Circuit Simulation," Proc. IEEE International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), pp. 345-348　2014

IRPS 2014

- T. Uemura, T. Kato, R. Tanabe, H. Iwata, H. Matsuyama, M. Hashimoto, K. Takahisa, M. Fukuda, K. Hatanaka, “Preventing Single Event Latchup with Deep P-well on P-substrate,” Proc. IEEE International Reliability Physics Symp., pp. SE.3.1-SE.3.4, 2014.

Journal

- T. Uemura, T. Kato, R. Tanabe, H. Iwata, J. Ariyoshi, H. Matsuyama, M. Hashimoto, “Exploring Well-Configurations for Minimizing Single Event Latchup,” Nuclear Science, IEEE Transactions on 61(6) 3282-3289 2014.
- H. Mori, T. Uemura, T. Yamazaki, T. Soeda, “Detection Technique with Alpha-tracking and Emissivity Comparison” Nuclear Science, IEEE Transactions on 61(6) 3438-3442, 2014.
- T. Kato, R. Akano, T. Uemura, Y. Watanabe, “Neutron Shielding Effect of Stacked Servers and Its Impact on Reduction of Soft Error Rate,” Nuclear Science, IEEE Transactions on 61(6) 3408-3415 2014.
- T. Yamazaki, T. Kato, T. Uemura, Y. Tada, K. Yamazaki, T. Soeda, T. Miyajima, Y. Kataoka, “Origin analysis of thermal neutron soft error rate at nanometer scale.” Journal of Vacuum Science & Technology B 2015

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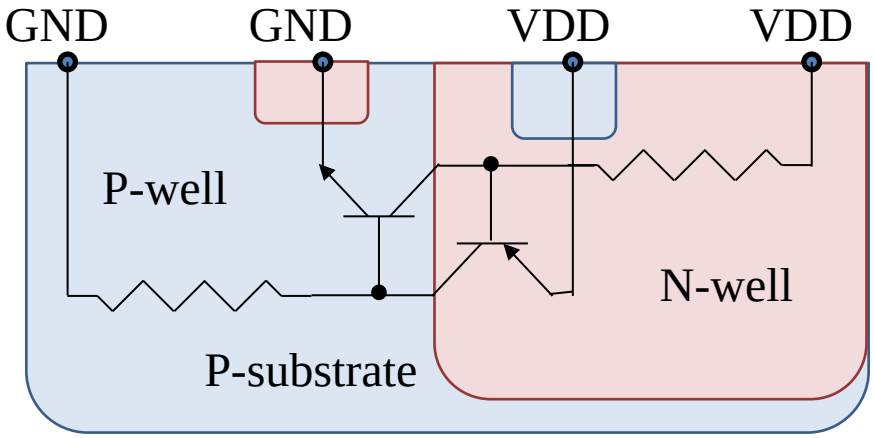
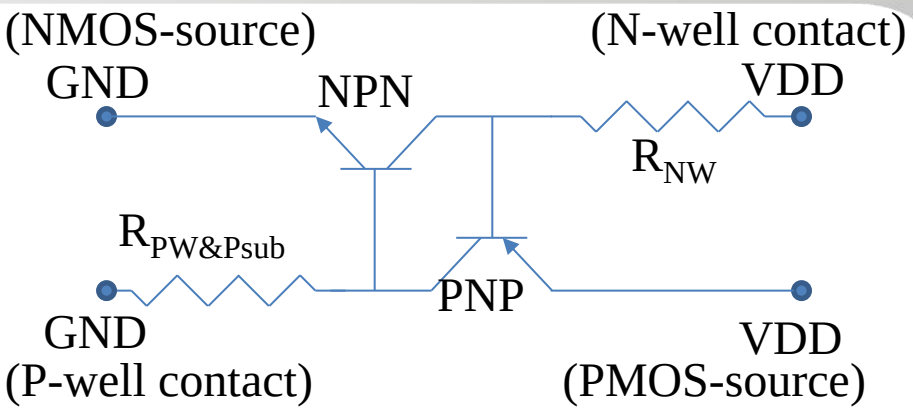
SEL対策技術

- T. Uemura, T. Kato, R. Tanabe, H. Iwata, H. Matsuyama, M. Hashimoto, K. Takahisa, M. Fukuda, K. Hatanaka, “Preventing Single Event Latchup with Deep P-well on P-substrate,” IRPS2014
- T. Uemura, K. Takashi, R. Tanabe, H. Iwata, J. Ariyoshi, H. Matsuyama, “Optimizing Well-Configuration for Minimizing Single Event Latchup,” NSREC2014

In this work,





- SEL
  - SEL is an abnormal high-current state in a device triggered by the passage of an energetic particle, & it results in the loss of device functionality [JEDEC]
  - shorts VDD and GND resulting in functionality loss
  - is caused by parasitic p-n-p-n bipolar activation triggered by an energetic particle
- SEL issues
  - One of the most important reliability issues on SRAM
  - Non-negligible SEL ratein commercial products at terrestrial environment
- Our approach for SEL prevention
  - Optimizing well-configuration (no design change)

Experimental procedure

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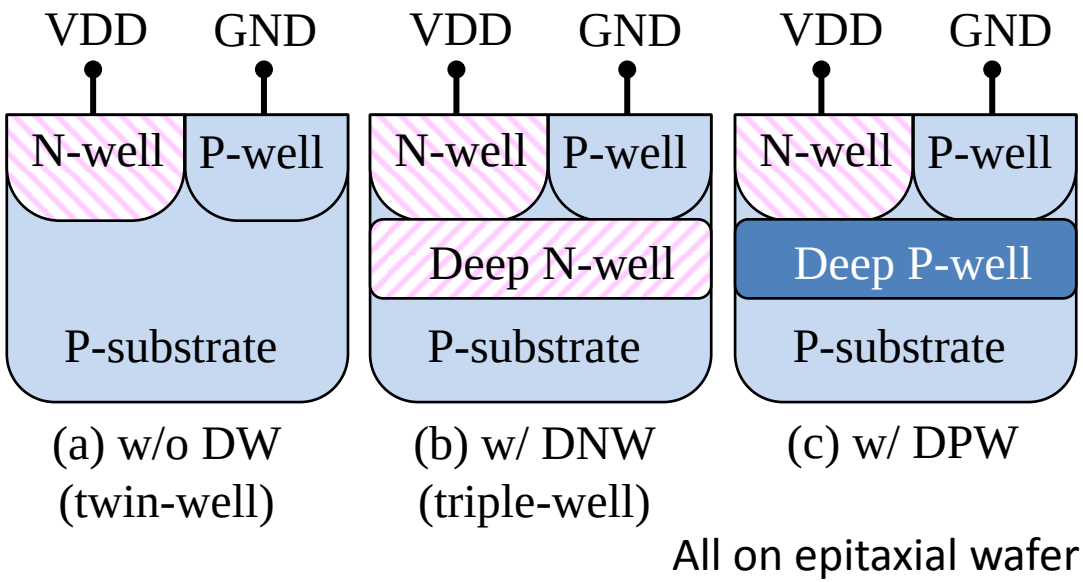

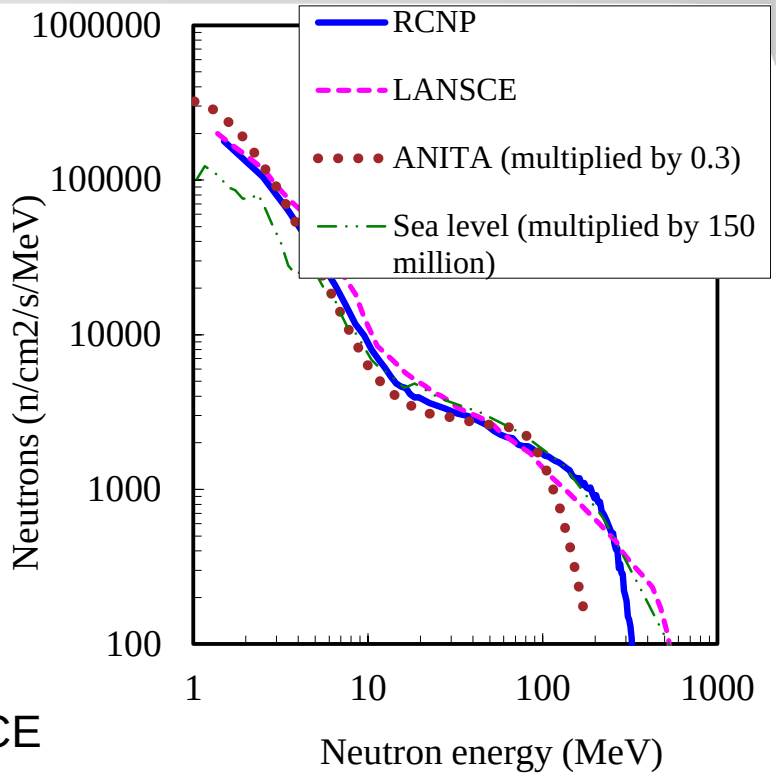

- Irradiation beam
  - Spallation neutron beam at RCNP, ANITA, LANSCE
- Test sample
  - 20 test chips by 11 designed 6T-SRAM array chip in 90 nm & 55 nm
  - In P-substrate epitaxial wafer assembled with plastic package with wire bonding
  - (a)Twin-well (changing dose amount), (b)Triple-well w/ DNW, (C)Triple well w/ DPW
- SEL observation
  - The occurrence of SEL was counted when unusual current was observed in power supply line, where the unusual current was assumed to be higher than the usual current by ten percent or more. For counting SEL, the current was monitored at five-second interval.

Dependence on well configuration (TEST-3)

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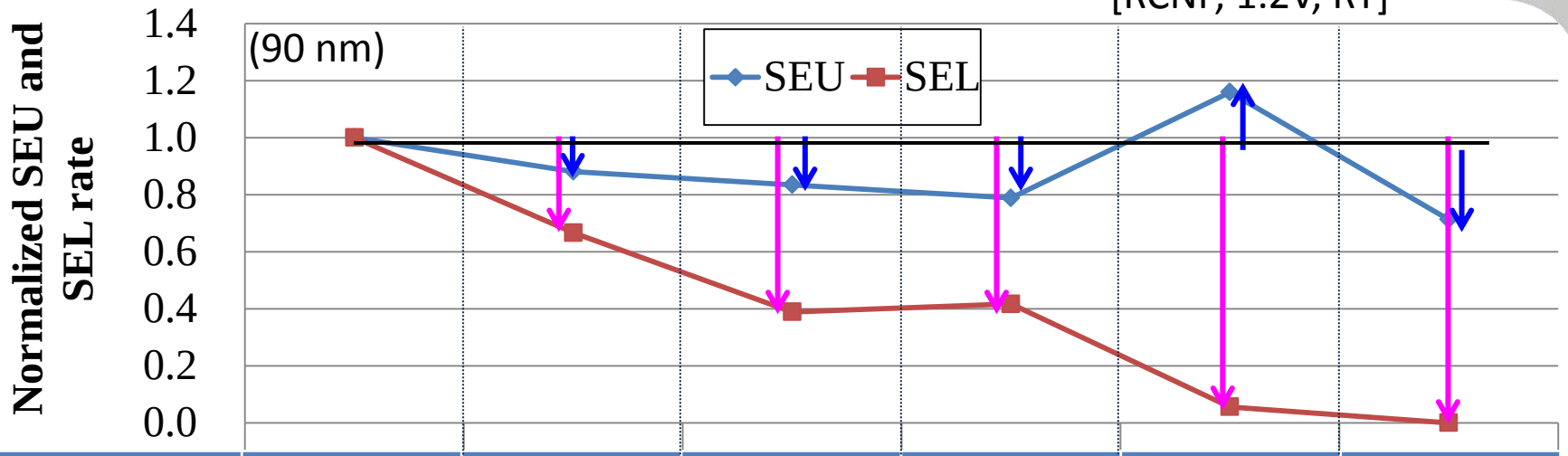
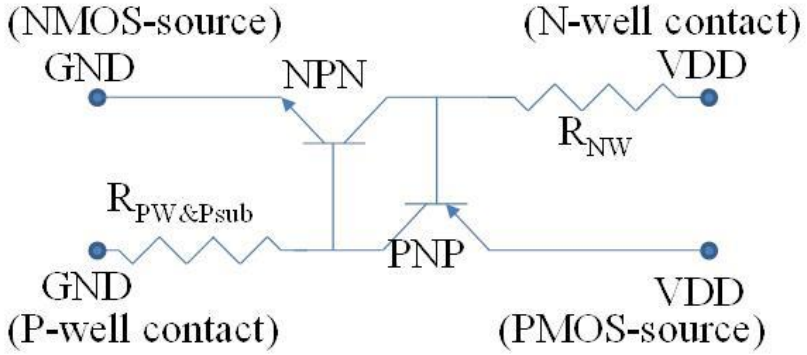
[RCNP, 1.2V, RT]



Wafer	W0	W4	W2	W6	W3	W1
N-well dose amount	1.0 (Normalized)	1.0	1.5	4.0	1.0	1.0
P-well dose amount	1.0 (Normalized)	1.2	1.5	4.0	1.0	1.0
Deep N-well (DNW)	No	No	No	No	Yes	No
Deep P-well (DPW)	No	No	No	No	No	Yes

- Higher dose rate: preventing SEL maximum 60%
- DNW: preventing SEL but SEU increase
- DPW: most effective for preventing SEL also SEU

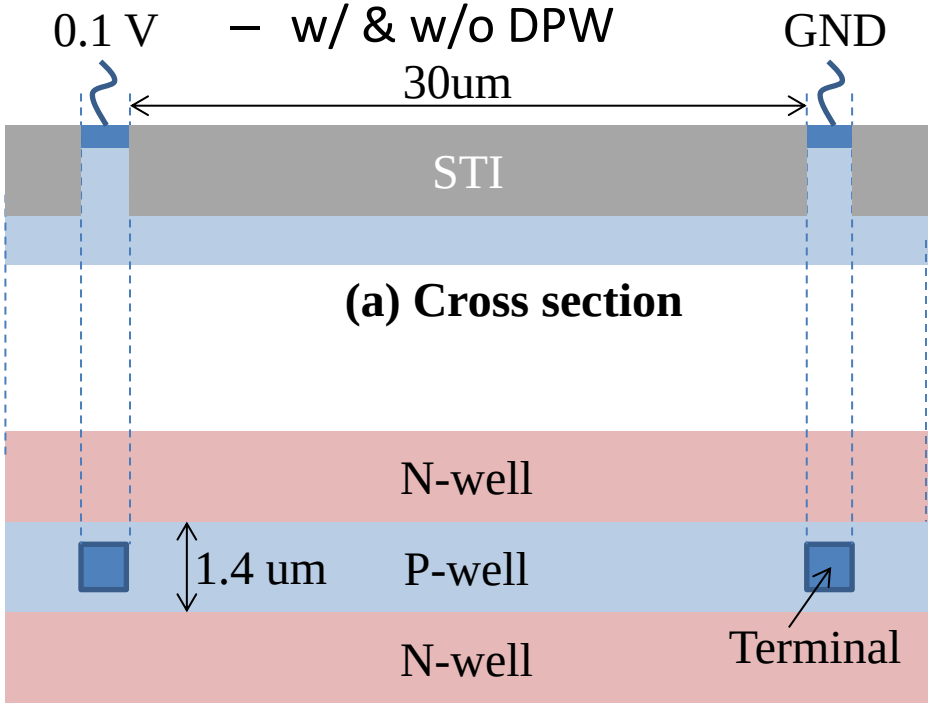
SEL prevention mechanism in DPW



- Well resistor measurement
  - Wafer probing
  - w/ & w/o DPW

Measured well resistance

	w/o DPW	w/ DPW
N-well	1.0 (normalized)	1.0
P-well	1.0 (normalized)	0.4



- P-well resistance w/ DPW was 60% lower than w/o DPW.
- stabilizes well potential and makes parasitic bipolar Tr. less active.
- SEL prevention!

Conclusion

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Well optimization can suppress SEL with some cost as following;

- Highly dose twin-well
  - SEL prevention (～0.4X)
  - Newly process unnecessary (only process tuning)
- Triple-well with DNW
  - High SEL prevention (0.01X ～)
  - SEU rate increase
  - Small cost (usual process option)
- Triple-well with DPW
  - Perfect SEL prevention (more than circuitry technique)
  - Additional cost for DPW process (unusual process option)

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中性子線量評価技術

- T. Kato, T. Uemura, H. Matsuyama, R. Akano, Y. Watanabe, “Neutron Shielding Effect of Stacked Servers and Its Impact on Soft Error Rate,” NSREC2014

Objective

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We explore the potential role of the server structure as a neutron shield and its impact on SER.

High-end server
Max. configuration
1,570 kg !!!

Our Approach

1. Shielding Simulation

Does the server structure effectively shield high energy neutrons ?
The neutron flux attenuation is estimated by Monte-Carlo simulation.

2. Neutron Measurement in a Building

Which is the more dominant factor in shielding, building or server structure ?
Combining neutron measurement with shielding simulation, the relative contribution of them to neutron shielding is analyzed.

3. SER Simulation

What is the impact of neutron shielding on SER ?
Assuming 28 nm SRAM cells implemented in CPUs, the possibility of SER reduction is investigated through full physical Monte-Carlo simulation.

Method 1: Shielding Simulation

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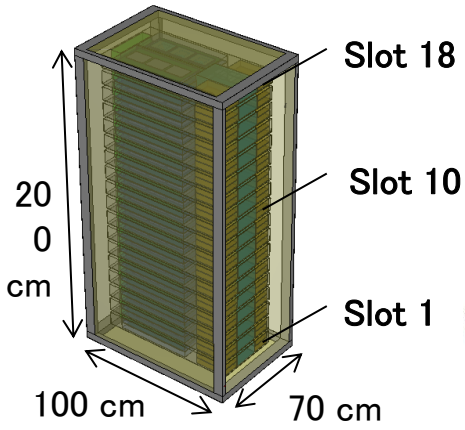
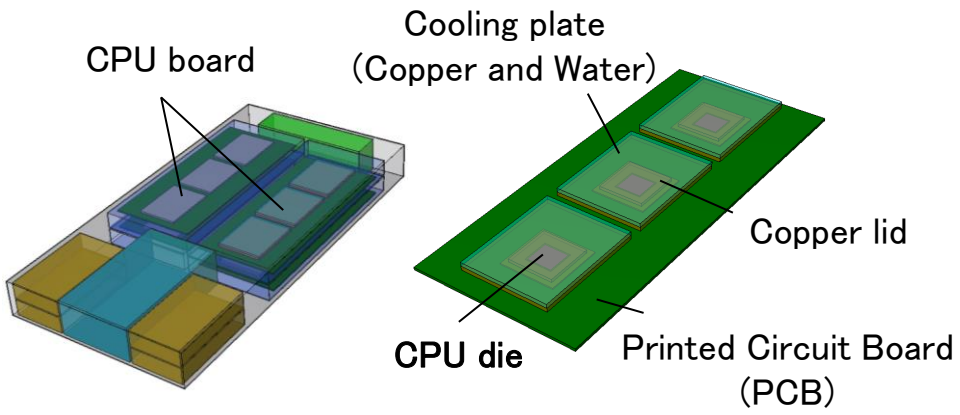
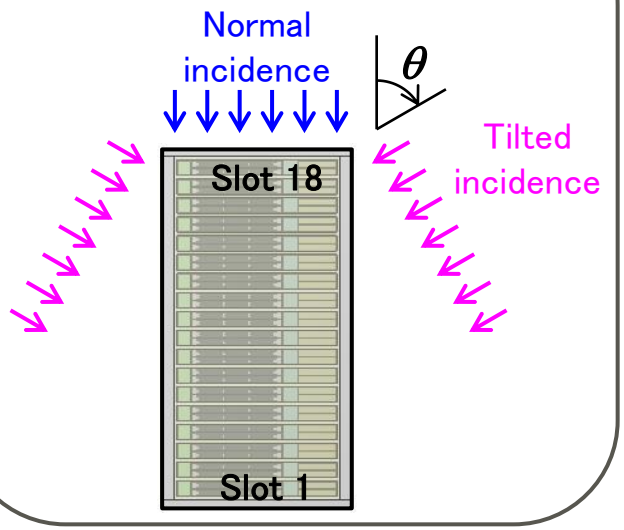
Model of Server Structure





Element	Weight [kg]
H	5
C	47
O	68
Al	139
Si	6
Cr	101
Fe	778
Cu	420

Irradiation Condition



- The weight and average density of the server structure is 1,570 kg and 1.1 g/cm^3, respectively.
- Calculation is conducted using the PHITS code [3].
- The server structure is irradiated to neutrons with energy between 1 MeV and 1GeV.
- We employ the energy spectrum of terrestrial neutrons given in JEDEC JESD89A [1].
- Both normal and tilted incidences are considered.
- Neutron flux attenuation is estimated by counting neutrons that arrive at CPU dice in each slot.

Method 2: Neutron Measurement

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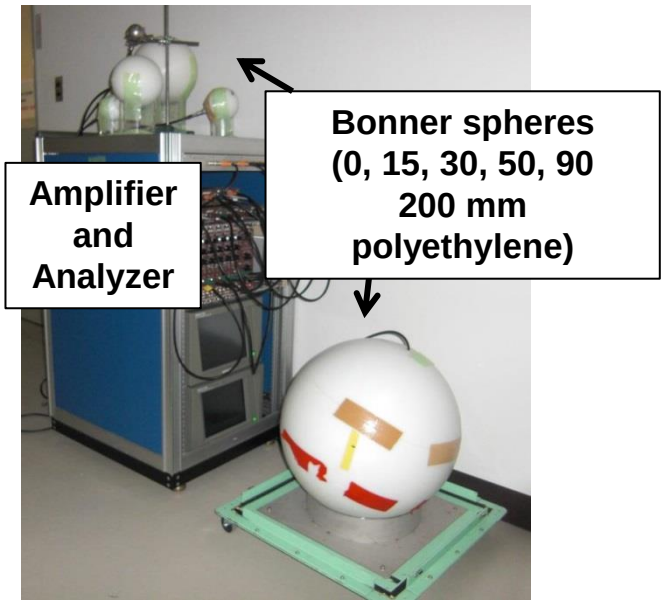
- Bonner sphere neutron spectrometer
  - Our spectrometer has six Bonner spheres.
  - Bonner spheres have polyethylene balls with different thicknesses of 0, 15, 30, 50, 90 and 200 mm, where 0 mm corresponds to a bare ^{3}He counter without polyethylene.
  - Our measurement covers the neutron energy range from 10 meV to 10 GeV.
  - The MAXED code is used for the accurate unfolding of measured data [6].



- Neutron measurement in a building
  - Neutron measurements are carried out in open air and in a five-story building at the Chikushi campus of Kyushu university, Japan.
  - The building is made of standard concrete with a density of 2.25 g/cm^{3}.
  - Each floor is separated by a 15 cm thick concrete slab.

Method 3: SER Simulation

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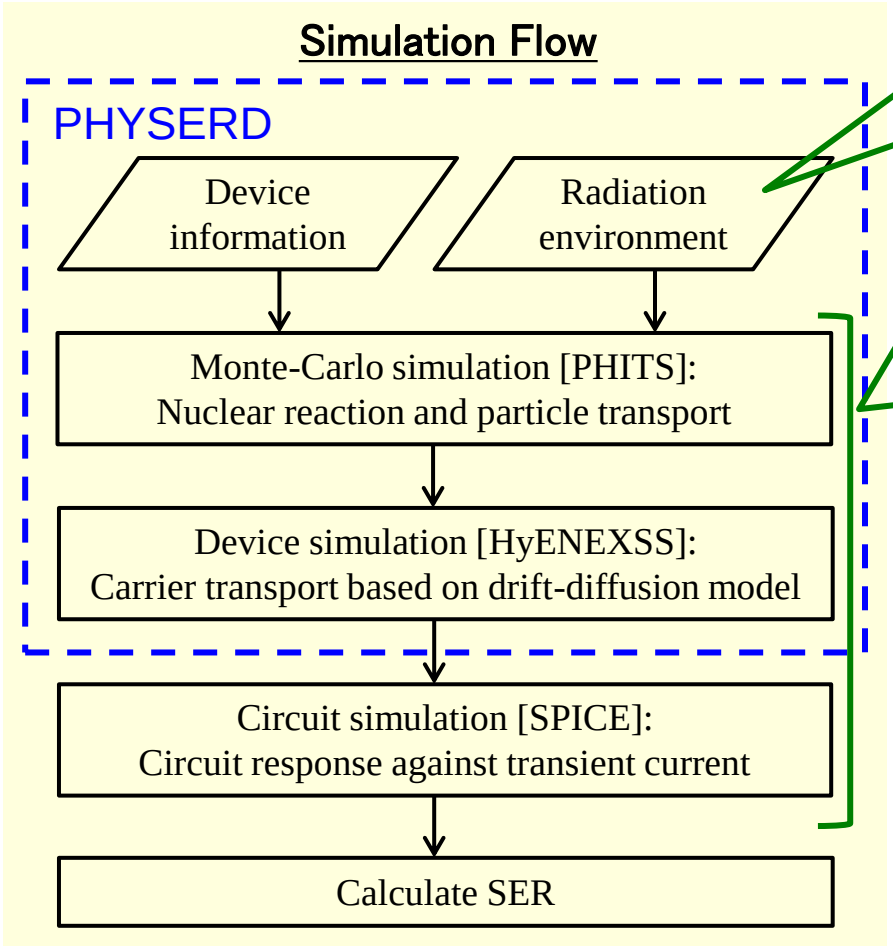
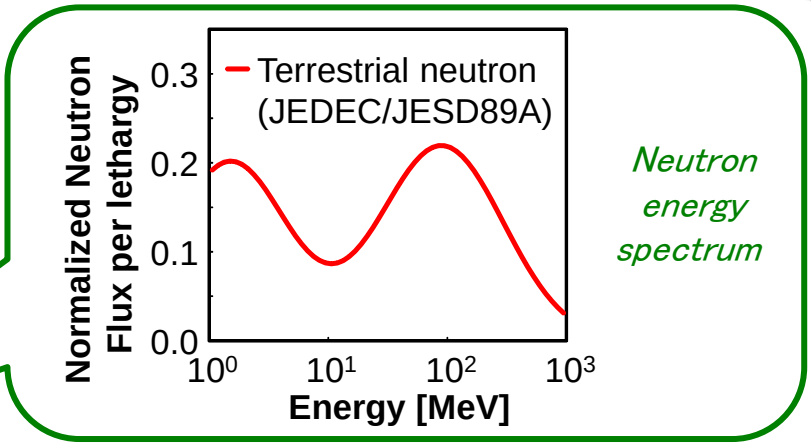
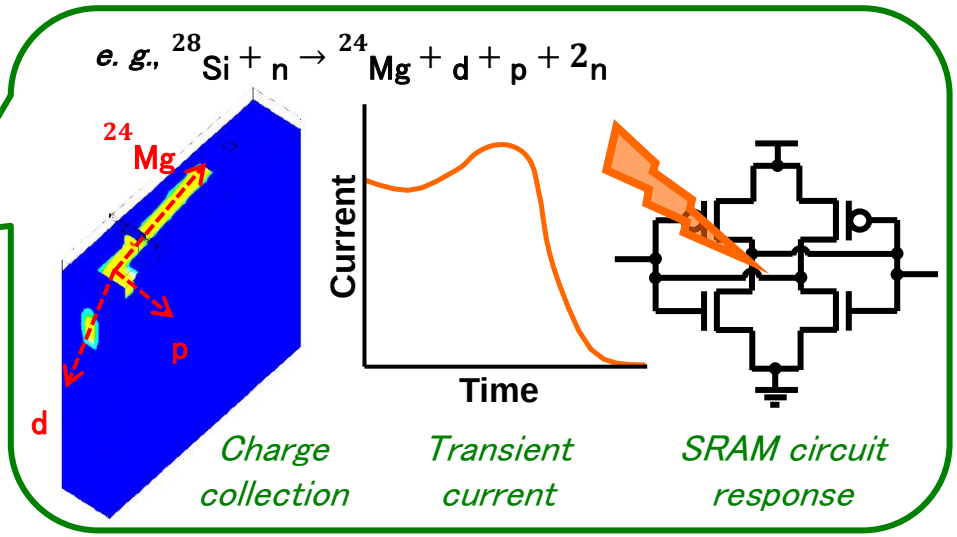
PHYSERD + Circuit Simulation

PHits-HYenexss integrated code System for Effects of Radiation on Devices, *developed by Abe et al., 2014* [4]







- Full physical Monte-Carlo simulation.
- Whether SEU occurs or not is determined by the voltage fluctuation at data node.
- Its accuracy has been verified [5].

Shielding Effect of Server Structure

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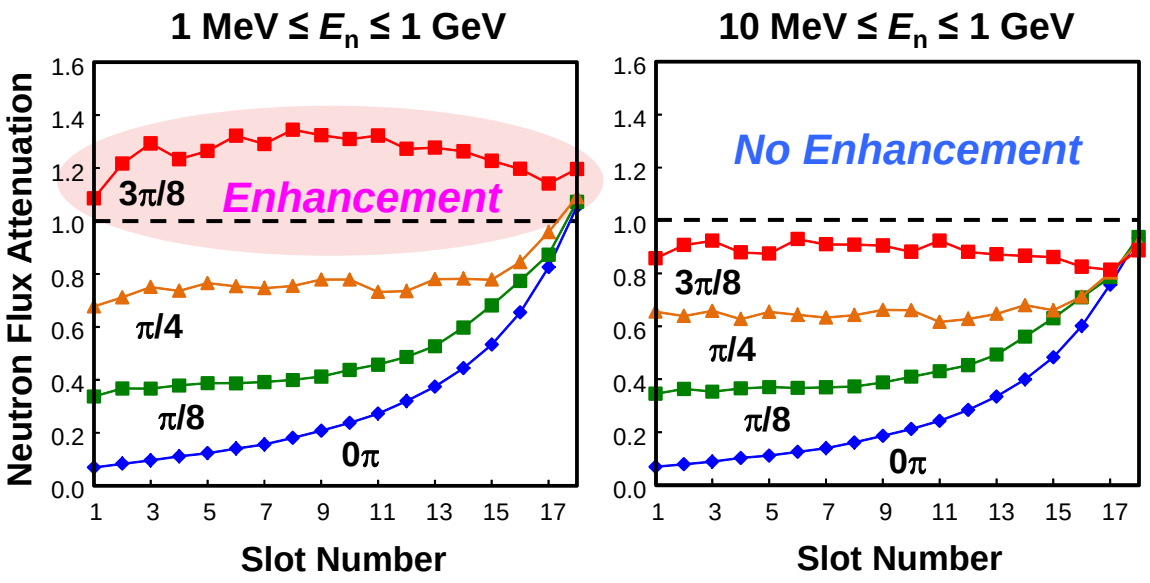
Neutron Flux Attenuation in Each Slot of Server Structure

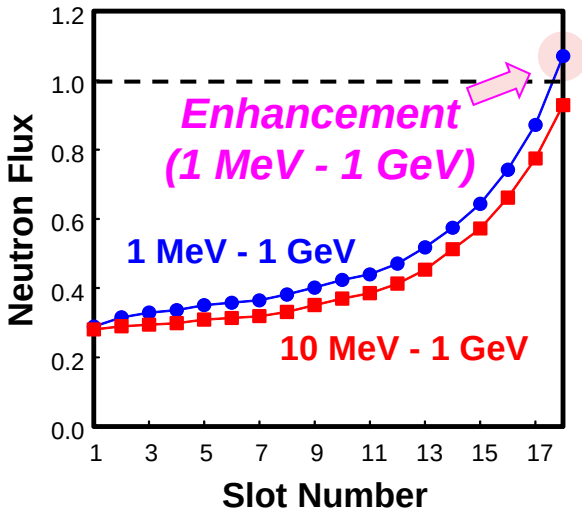
Flux attenuation at various incident angles

$\theta = 0\pi$ (normal), $\pi/8$, $\pi/4$, $3\pi/8$



Angle-averaged attenuation

$\cos^3$ variation with respect to θ for terrestrial neutrons [7]



- The server structure significantly attenuates neutron flux.
- Flux, especially at tilted incidence, enhances due to scattered neutrons below 10 MeV.
- Angle-averaged flux also shows flux enhancement in slot 18 for 1 MeV - 1 GeV.
- We need to pay attention to such enhancement because recent devices show the increase in SER sensitivity to neutrons below 10 MeV [8].

Shielding Effect of Building

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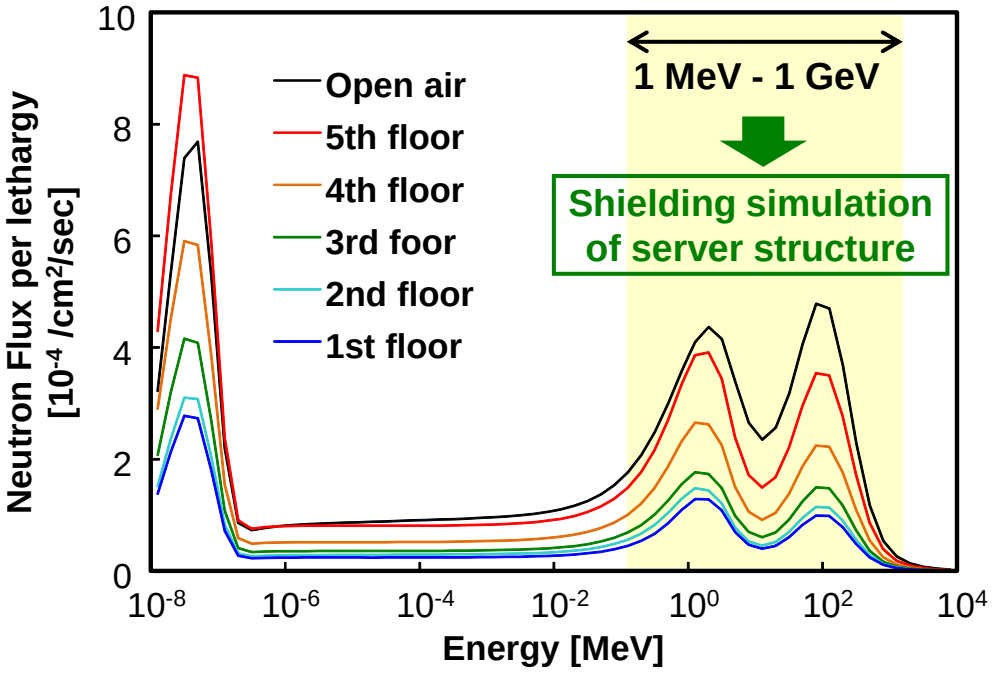
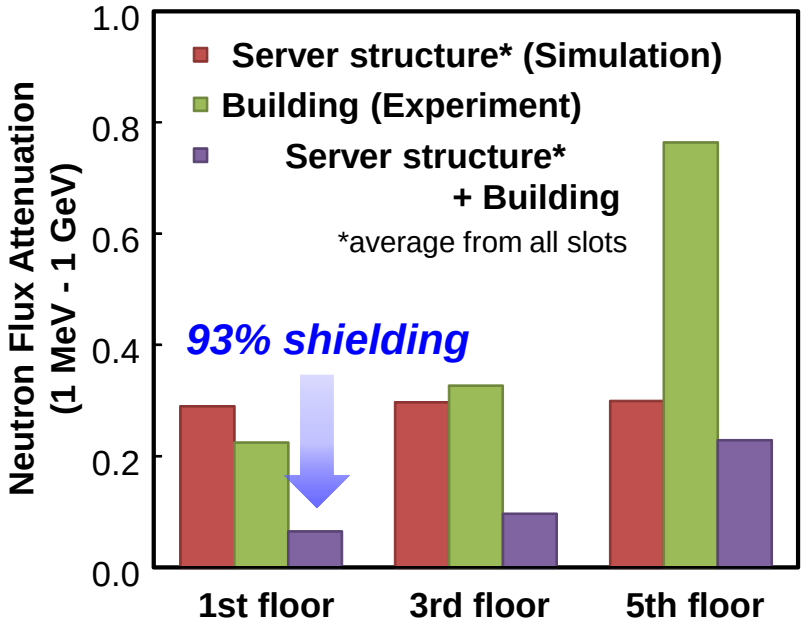
Neutron Flux Attenuation at Each Floor of Building

Energy spectra measured in the building



Flux attenuation in the building



- Terrestrial neutron spectra and its attenuation are successfully identified in the building.
- Measured spectra between 1 MeV - 1 GeV are used for shielding simulation of the server structure located in the building.
- Neutron flux attenuates mainly due to the server structure at upper floors.
- Neutron flux is shielded by 93% in the server structure located at 1st floor.

Impact on Soft Error Rate

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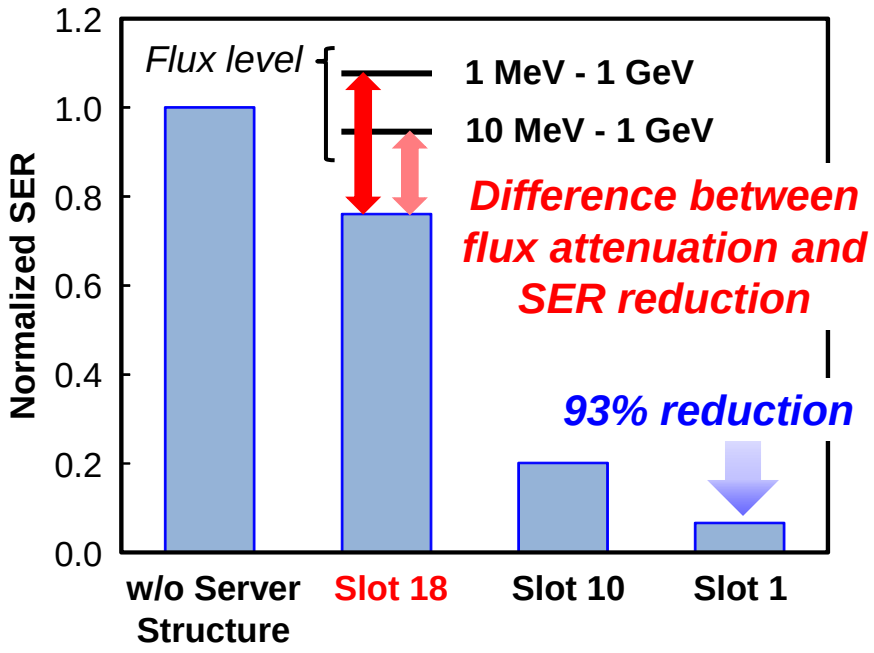
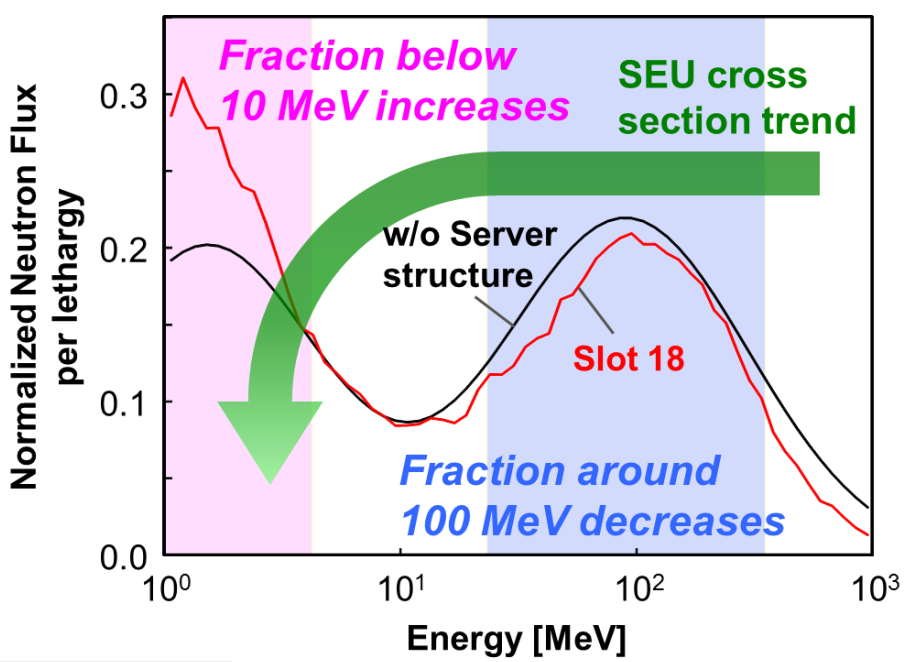
SER Reduction due to Shielding Effect of Server Structure





- SER is significantly suppressed due to the shielding effect of the server structure.
- The server structure also causes the distortion of the neutron energy spectrum.
- In addition to flux attenuation, the distortion of the energy spectrum is responsible for SER reduction.

$$\text{SER} = \int \varphi(E)\sigma_{\text{SEU}}(E)dE$$

differential flux *SEU cross section*

Enhanced SER reduction

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α線量測定技術

- H. Mori, T. Uemura, H. Matsuyama, T. Yamazaki, T. Soeda, “Development Detection Technique with Alpha-Tracking and Comparison of Emissivity,” NSREC2014
- T. Yamazaki, H. Mori, T. Soeda, and T. Uemura, “Structure Optimization of Solid-State Detector for Detection of Low-Dosage Alpha Rays,” TNS(submitted)

Objective

Alpha particles from IC materials is one of main source for SEU in terrestrial environments.

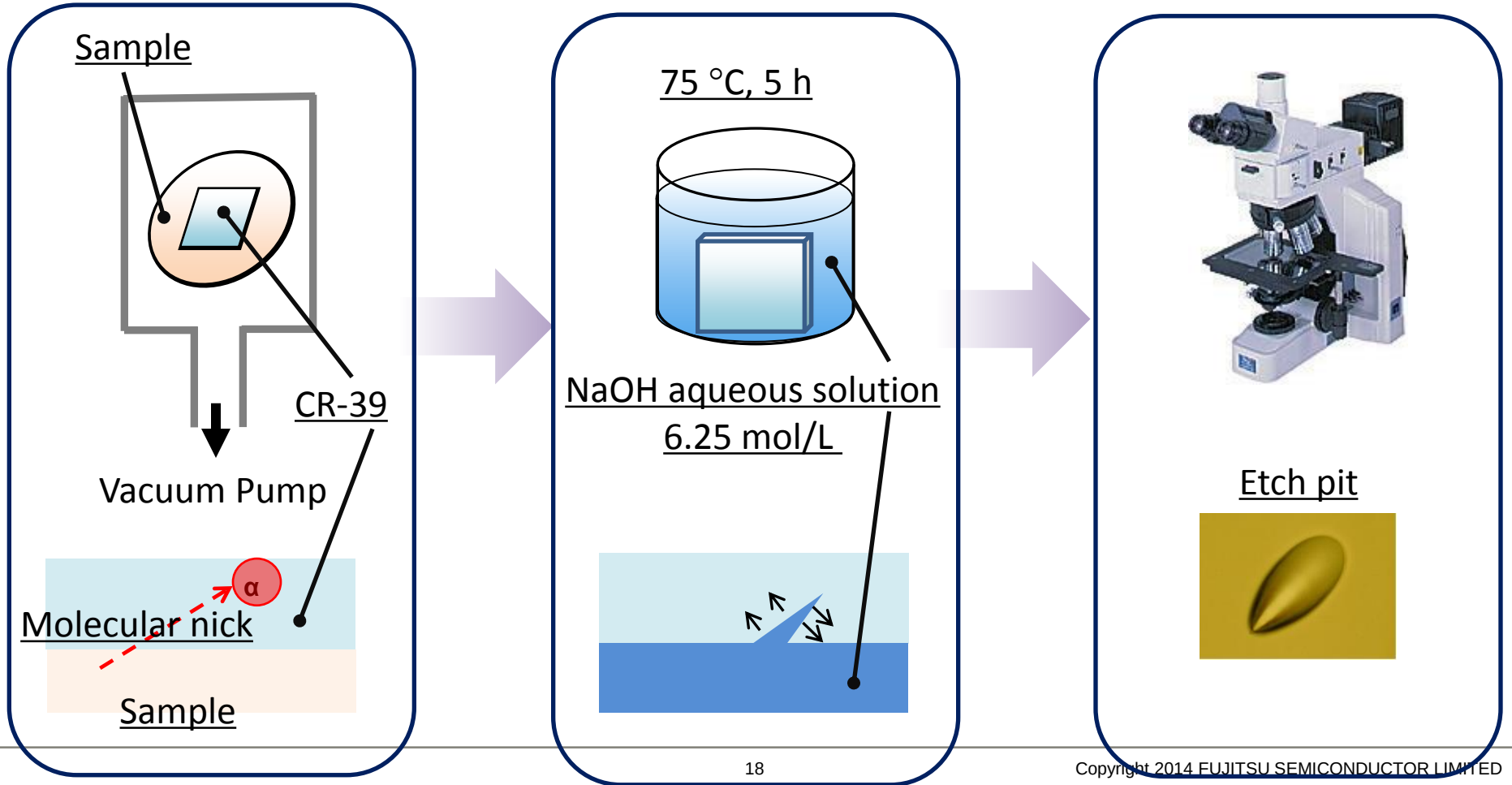
- It is necessary to achieve a low alpha-particle detection limit.
  - Low-alpha materials reduce alpha-induced SEUs in IC.
  - For selecting low-alpha materials.
- A low background environment is necessary.

We adopt an alpha-tracking technique in vacuum and investigate suitable conditions for minimizing the detection limit of this technique.

Alpha-tracking technique in vacuum

- Detector: CR-39 (Plastic polymer)
- Exposure environment: vacuum
- Detector method in exposure: face-to-face contact

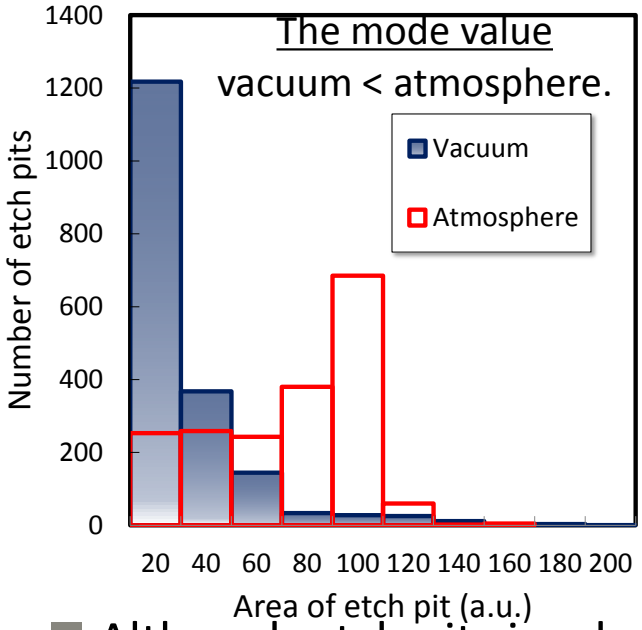
Achieve a low detection limit even with a small sample size (~100cm^2).

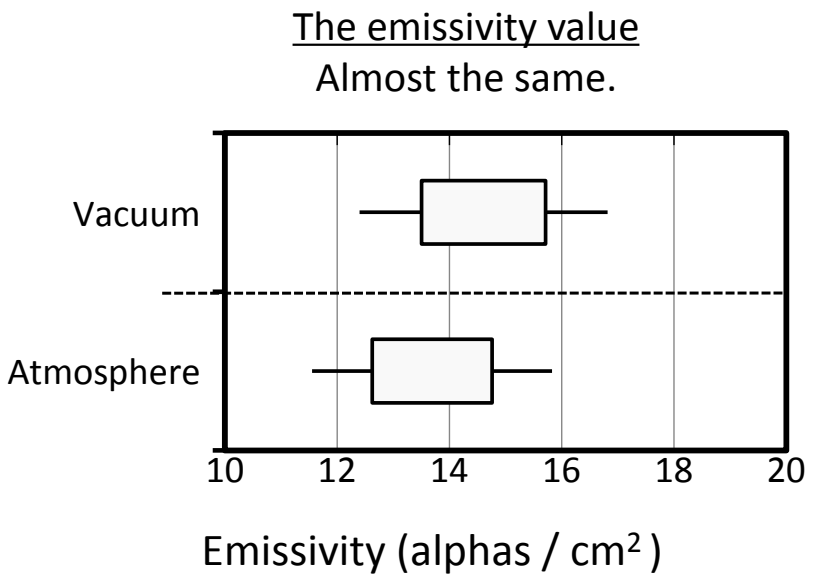


Influence of vacuum on alpha-tracking

- The sensitivity of CR-39 decreases under **irradiation in vacuum** or **storage in vacuum after irradiation**.

- Experiment 1: irradiation in vacuum
  - Exposure source: solder plate
  - Exposure time:24 hour (in vacuum & air)
  - We detect pit count & pit size.





- Although etch pit size decreases in vacuum, we can count the number of pits.

Influence of vacuum on alpha-tracking

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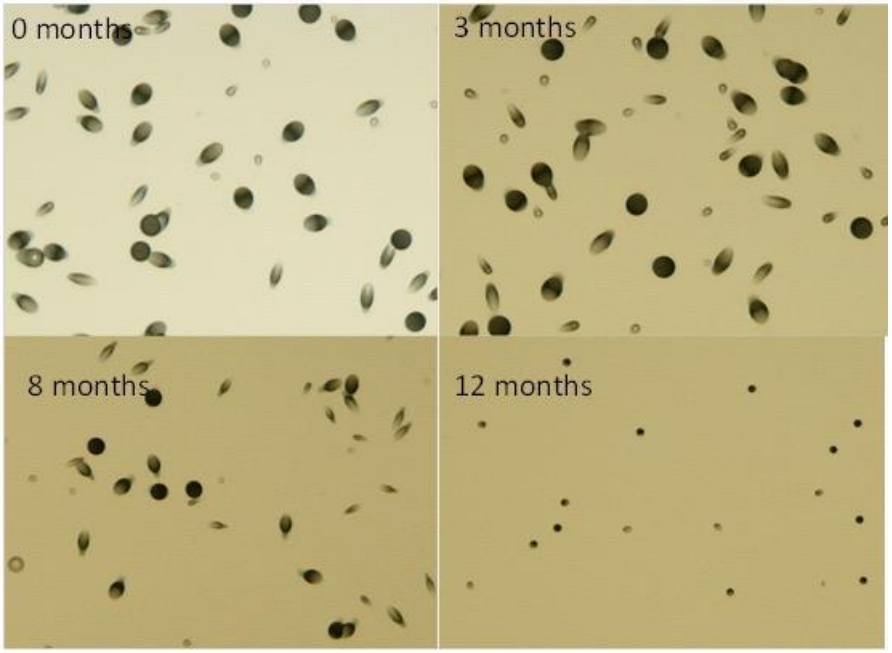
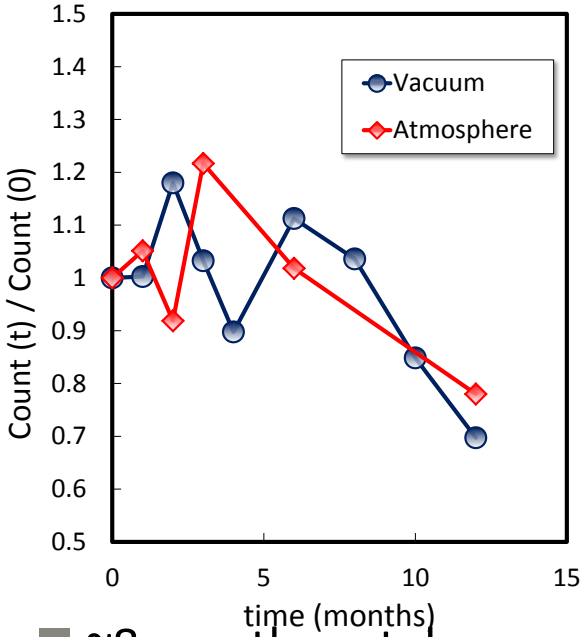
- Experiment 2: storage in vacuum after irradiation.
  - Exposure source: ^{241}Am (3 kBq)
  - Exposure time: 40 second
  - Storage time: ~12 months(in vacuum & in atmosphere wrapped by a fiber cloth)

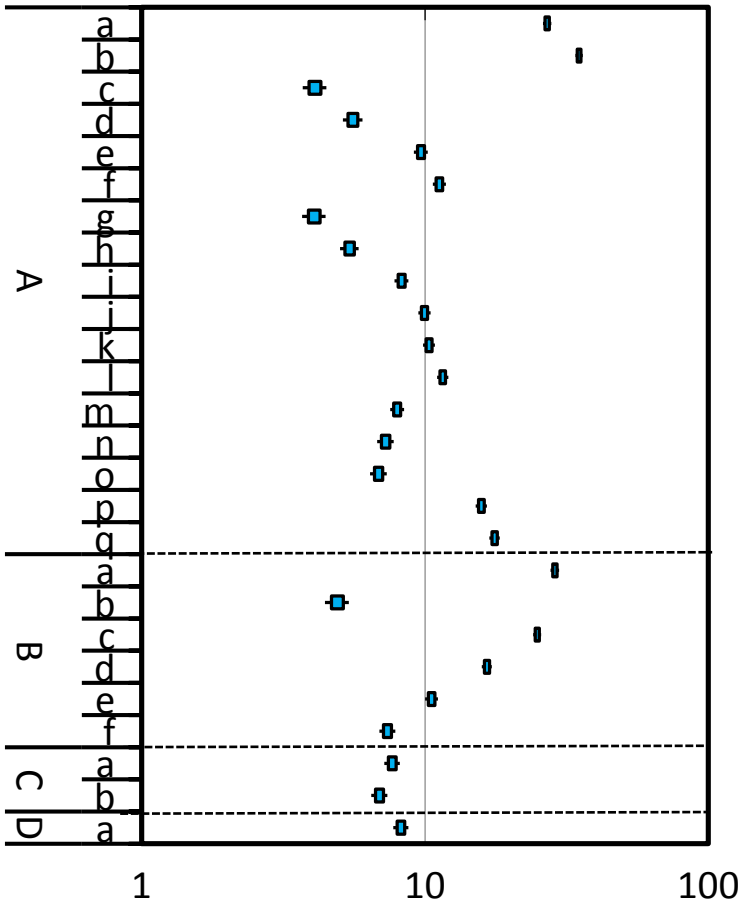




  - ~8 month: not decrease
  - 12 months: 70% decrease
- The maximum exposure duration for accurate measurement is 8 months.
- The detection limit is **0.049 alphas/kh-cm²**, for 8months exposure and 0.5pits/cm² initial pits.

Alpha emissivity of LSI materials: mold resin for package

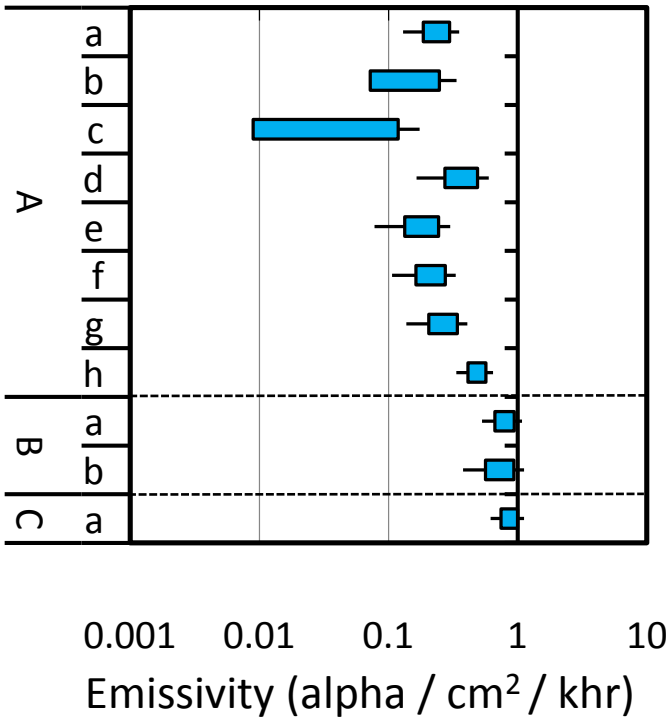
Normal resin



Emissivity (alpha / cm² / khr)

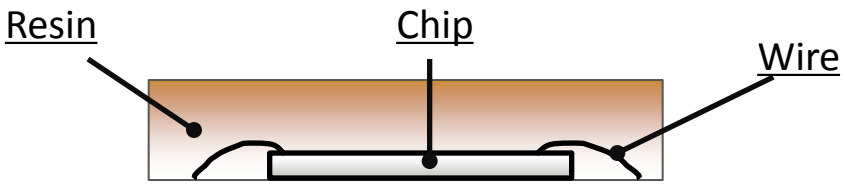
Capital letter: vendor.
Lowercase letter: product

Low-alpha resin



Emissivity (alpha / cm² / khr)

Exposure time: 3months



Measurement alpha emissivity: Other materials

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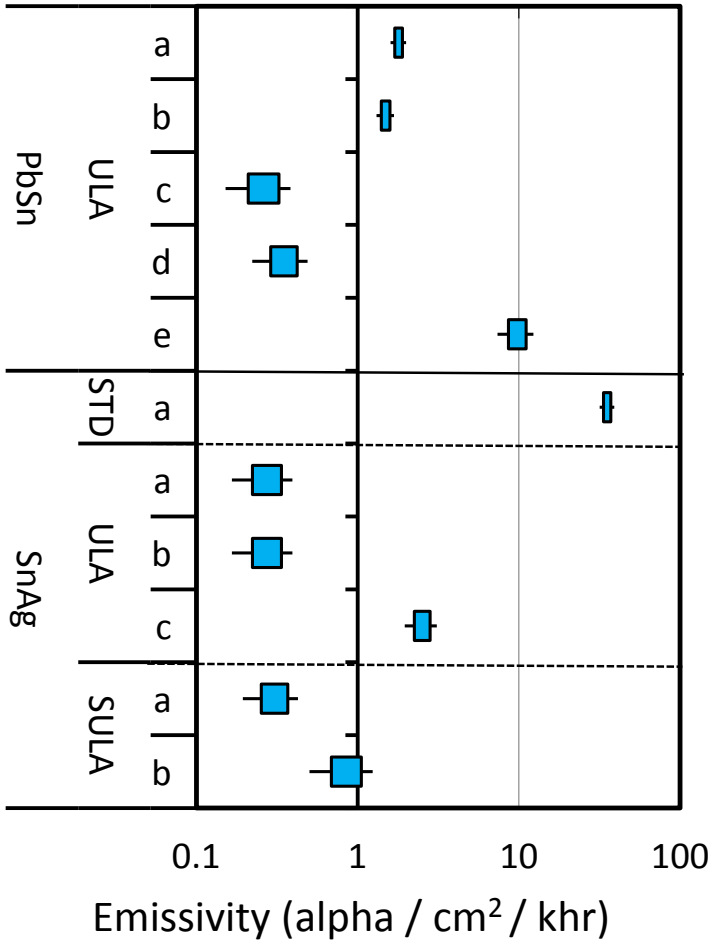
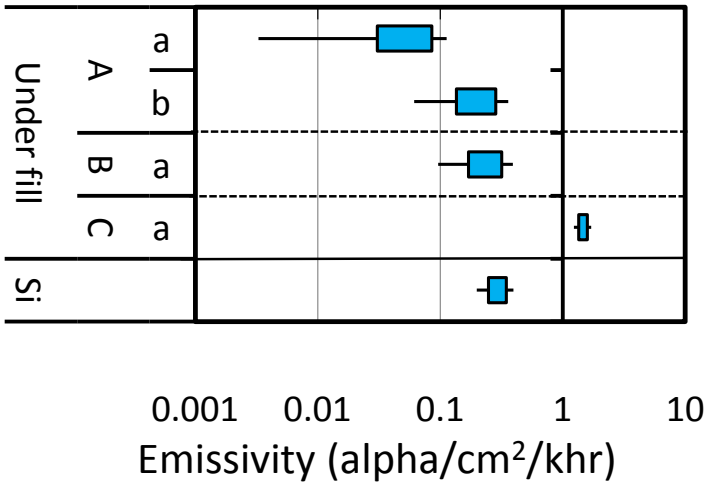
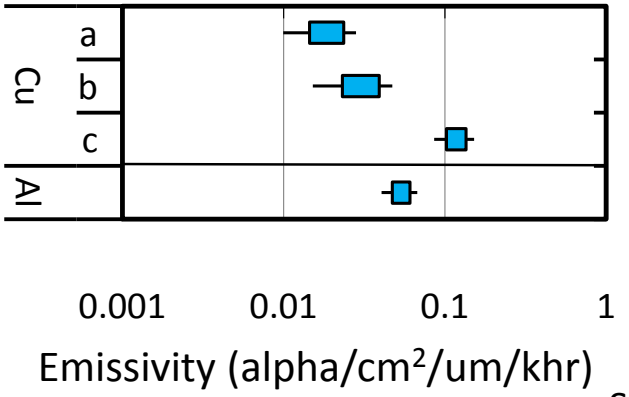
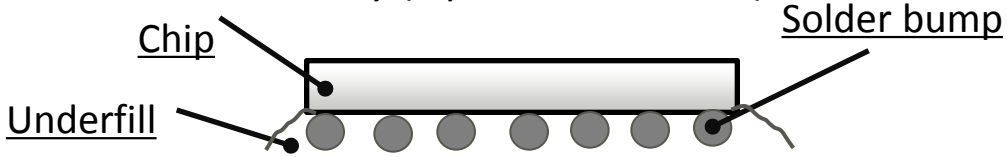
Solder



Underfill and chip materials







αトラッキング法の検出効率について

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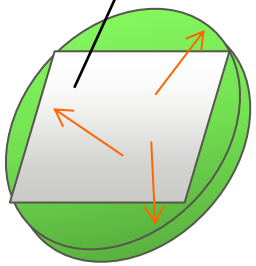
《現状》

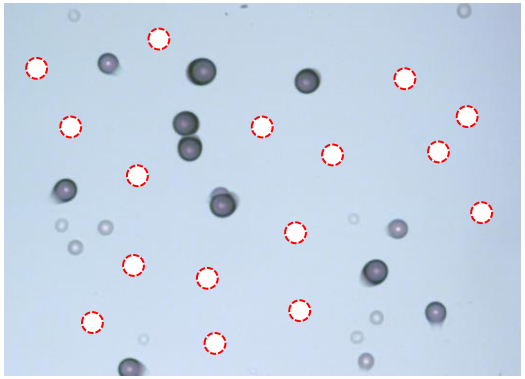
固体検出器



放射線をピットとして
記録する高感度方式

しかし実際は・・・

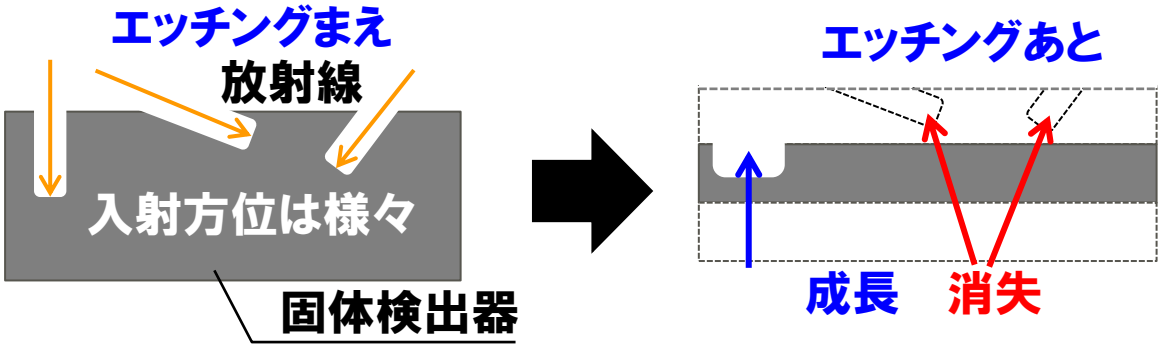
標準線量と一致せず



エッチング工程で
ピットの半数が消失している

固体検出法の利点を
活かせてない！

《原因》



《新たな課題》

検出効率を何とか
改善できないか.

検出効率の改善

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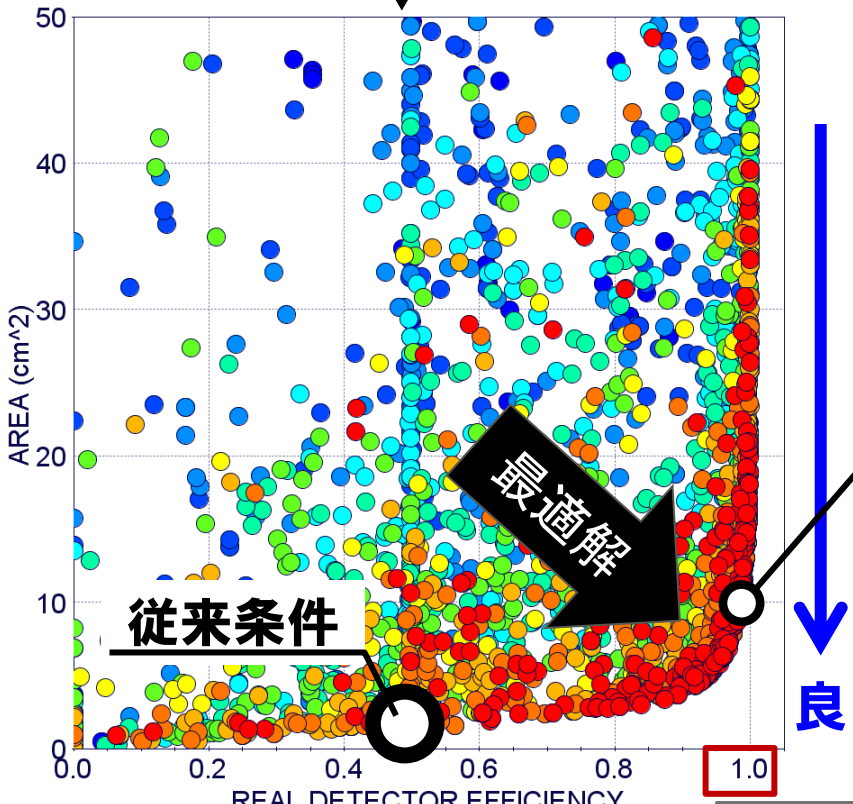
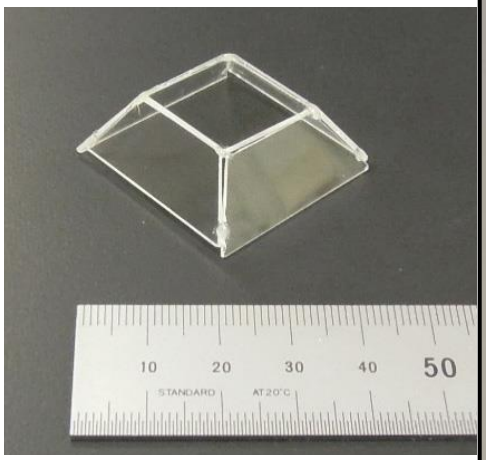
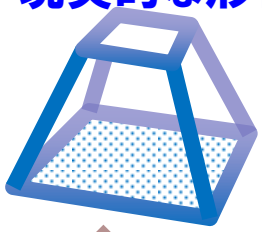
直付け方式(従来法)



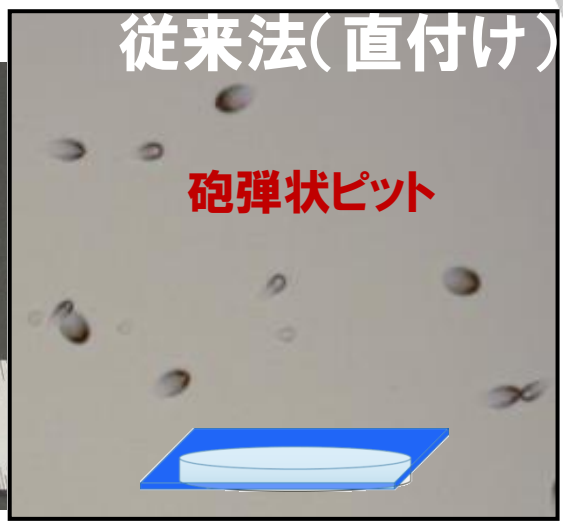
改善方式

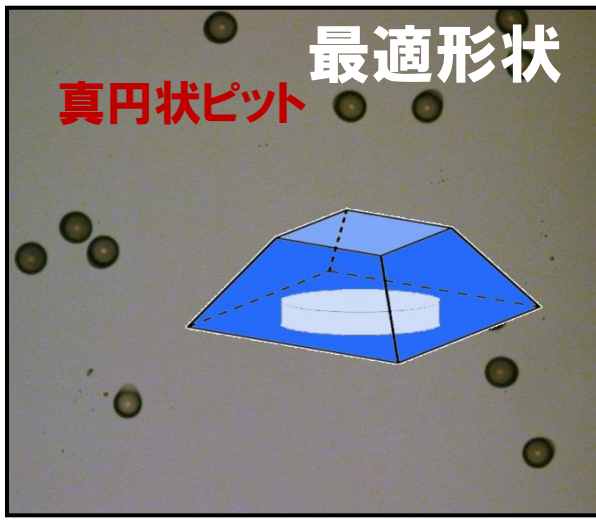


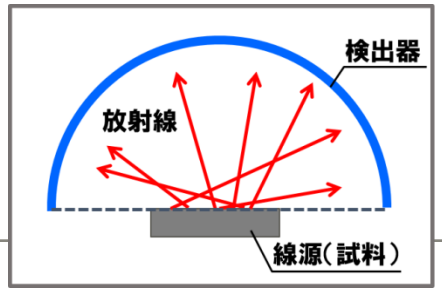
現実的な形状(錐台)



理想的な形状(球)







砲弾状ピットが消失 → 垂直入射

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Simulation評価技術

- T. Kato, T. Uemura, H. Matsuyama, "High-Accuracy Estimation of Soft Error Rate using PHYSERD with Circuit Simulation," SIAPD2014

Outline

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- **Background**
  - Soft error phenomenon
  - Problems in conventional soft error simulator
  - What is PHYSERD?
- **Simulation Method**
  - Two simulation frameworks
- **Results**
  - Comparison with experimental data
  - Some detailed analysis
- **Summary**

What is Soft Error?

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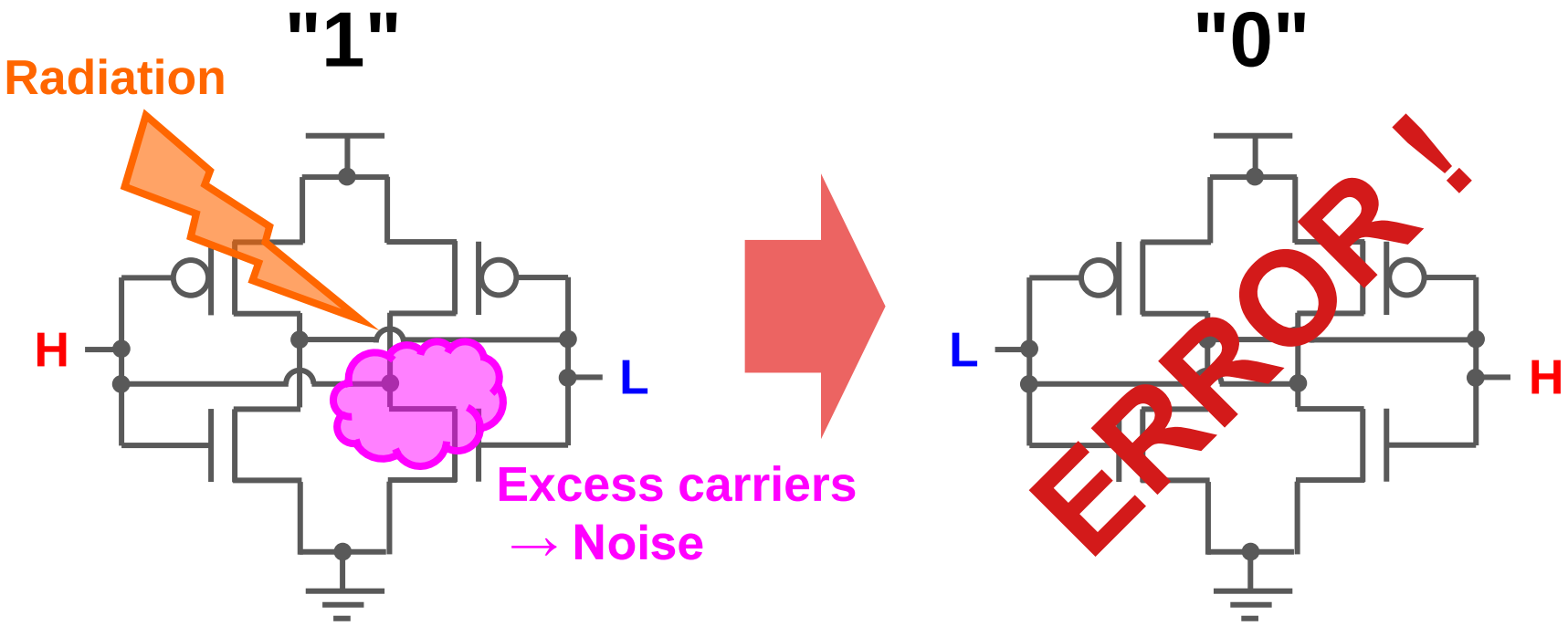
- Soft errors are nondestructive errors induced by radiation.
  - Soft error in SRAM



- **Single Event Upset (SEU)**
- **Soft Error Rate (SER)**

SEU is one of critical issues in device reliability.

Radiation Environment

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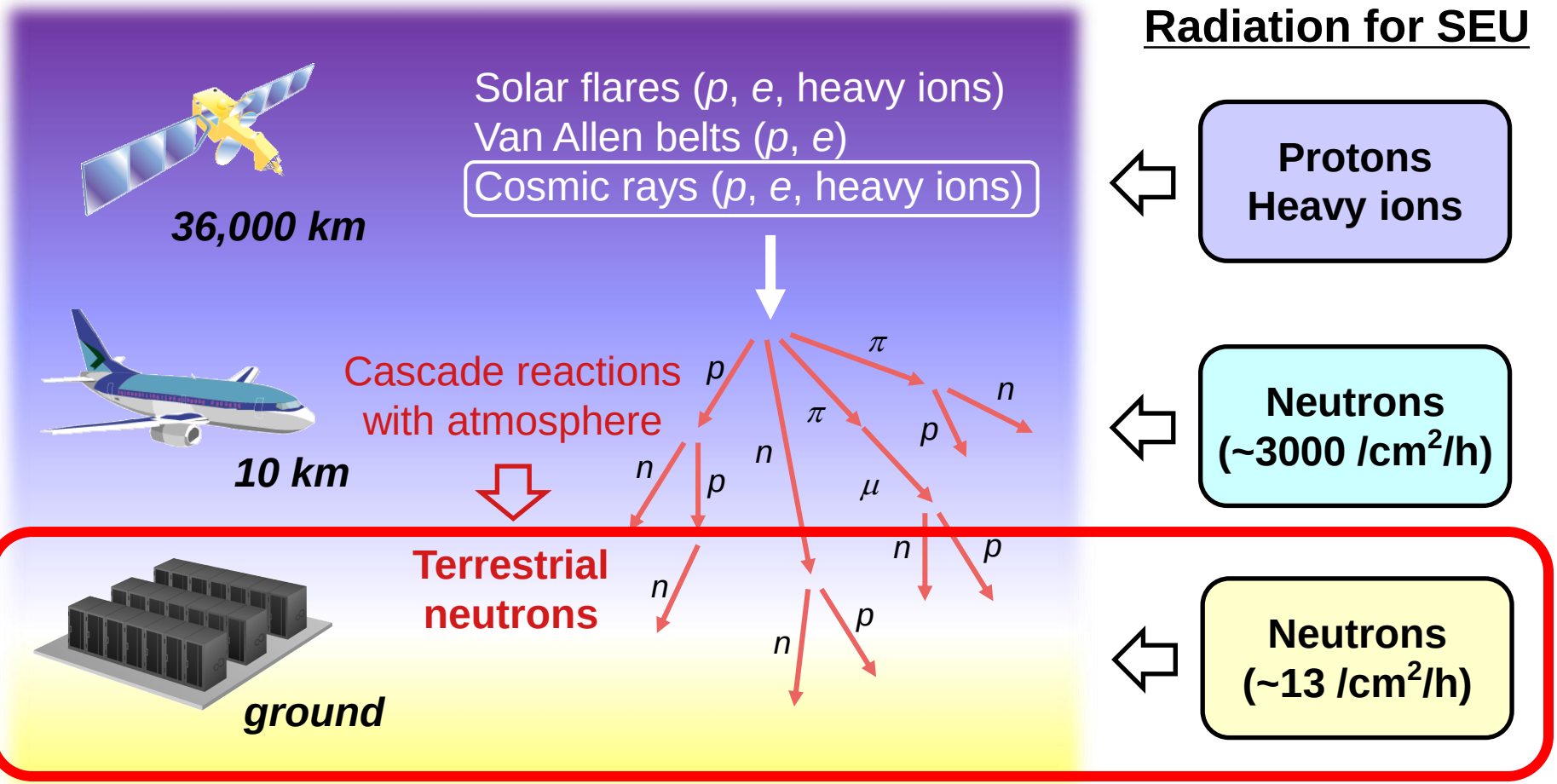
- Different locations lead to different radiations.



We need to consider SEU induced by terrestrial neutrons.

Terrestrial Neutron-Induced SEU

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Mechanism

Terrestrial neutrons

↓

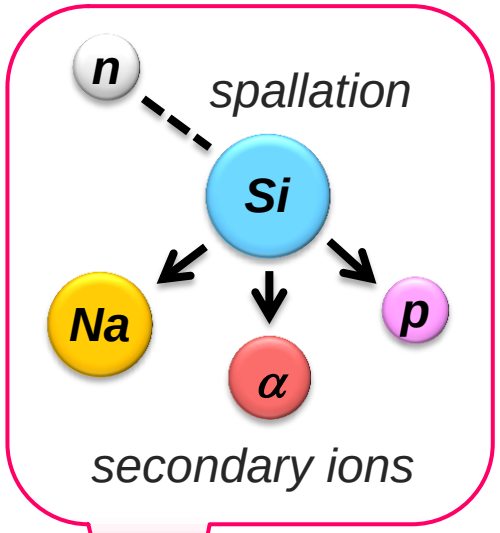
Nuclear reactions with component materials.
→ **Secondary ions**

↓

Secondary ions deposit charges in devices.
→ **Transient currents**

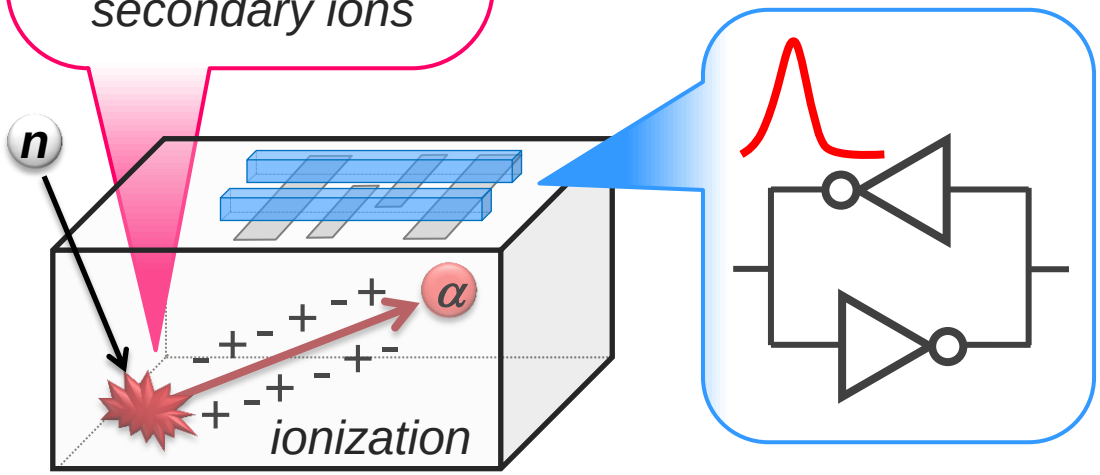
↓

SEU → SER



- ✓ **Neutron environment**
- ✓ **Nuclear reaction**
- ✓ **Particle transport**

- ✓ **Carrier transport**
- ✓ **Circuit response**



Performing SER simulation requires a wide range of fields.

Conventional SER simulation in FSL

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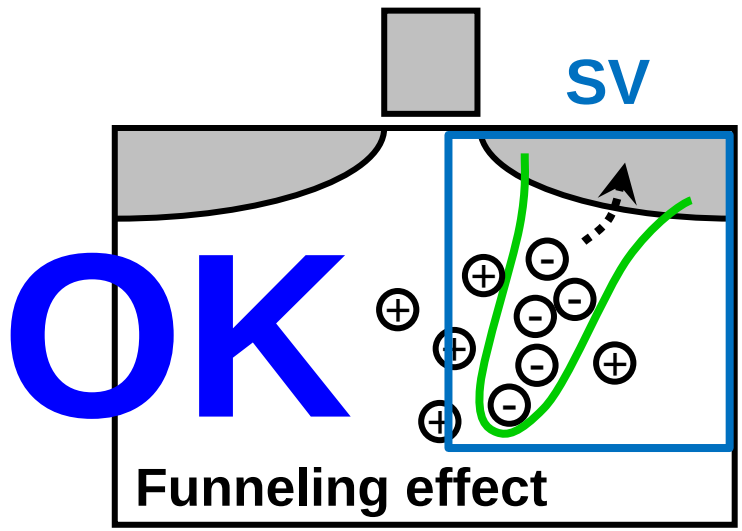
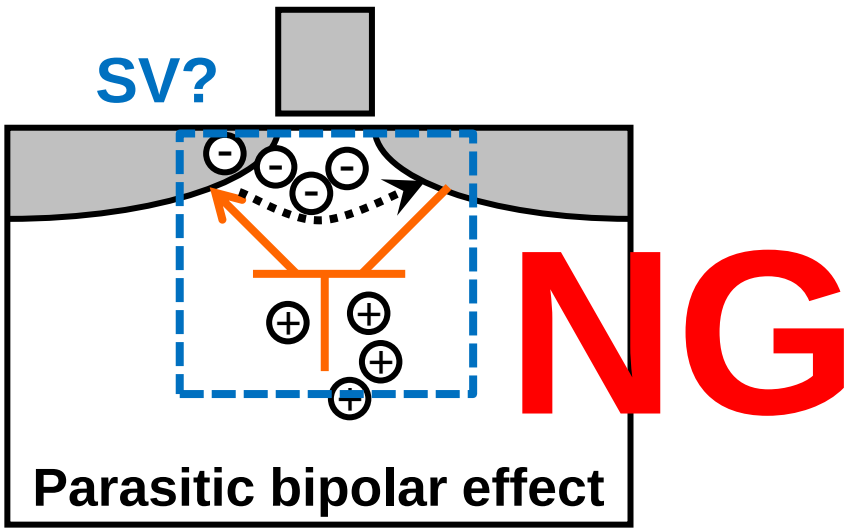
- NISES: Neutron Induced Soft Error Simulator
  (*tosaka et al.,SISPAD 1997 and 2007*)
  - NISES is based on **sensitive volume (SV) approximation**.

The validity of SV is limited.

Direct charge collection



Indirect charge collection



Parasitic bipolar effect becomes more active with scaling down.

→ **New simulation framework beyond SV approximation**

What is PHYSERD?

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- Multi-scale Monte Carlo simulation code system
  (*Abe et al.*, *Trans. Nucl. Sci., 2012*)

PHYSERD: PHits-HYenexss integrated code System for Effects of Radiation on Devices

Stage	Component
Nuclear reaction and particle transport	Monte Carlo particle transport code (PHITS, JAEA)
Carrier transport	3D mesh generator (TAKOMESH, Tsukuba Univ.)
	3D TCAD simulator (HyENEXSS, SELETE)
Circuit response	Critical charge method.

Event-by-event TCAD calculation
→ ***Beyond SV approximation***

Weak consideration of circuit
→ ***Is improvement needed?***

How accurate is PHYSERD in SER estimation?

Simulation Flow

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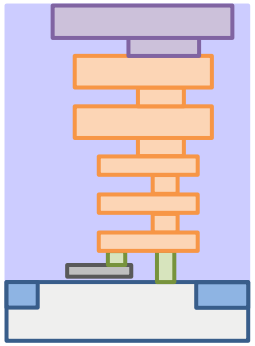
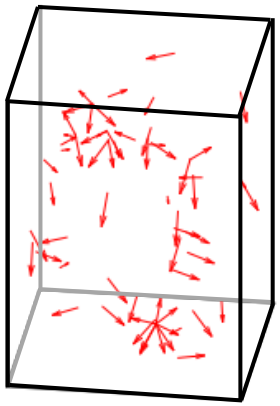
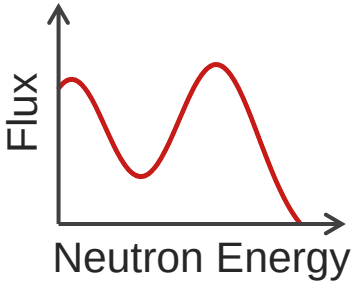




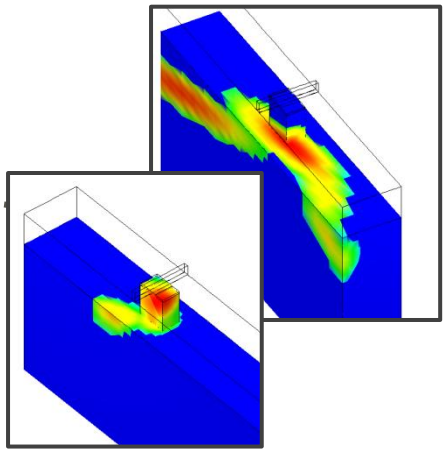
Device information

Radiation environment



Monte-Calro simulation [PHITS]
Nuclear reaction and particle transport

Device simulation [HyENEXSS]
Carrier transport



Collected charge

Transient current waveform

Critical charge (Q_{crit}) method

Waveform method [SPICE]

SER

SER

Original PHYSERD
II
Q_{crit} method

PHYSERD + Circuit sim.
II
Waveform method

SEU determination

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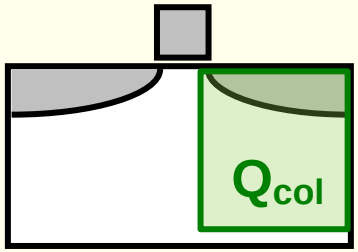
NISES

SV approximation

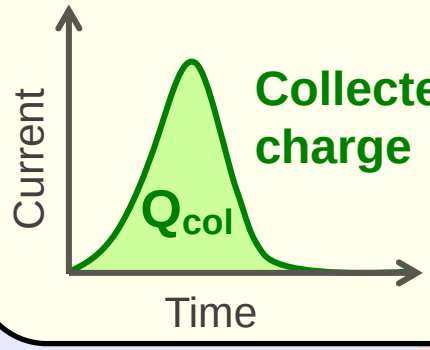


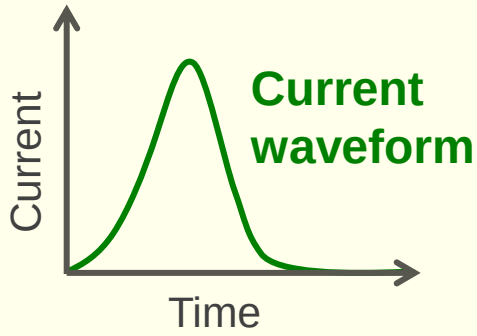
Collected charge

PHYSERD

PHYSERD + Circuit Sim.

Transient analysis (TCAD)





Critical charge (Q_{crit}) method

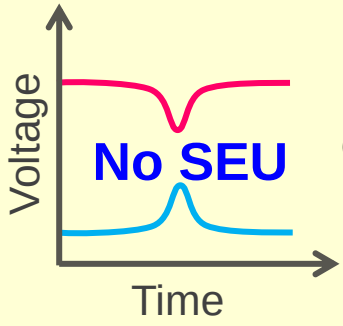
Q_{crit} is a minimum charge required for SEU.

$Q_{col} < Q_{crit}$ ⇩ No SEU

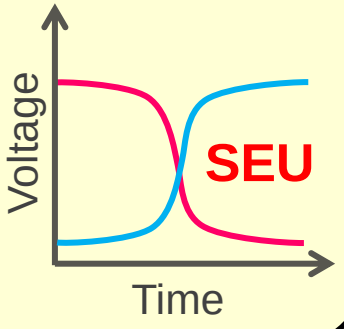
or

$Q_{col} \geq Q_{crit}$ ⇩ SEU

Waveform method



or



Which is an appropriate method, Q_{crit} or waveform?

Comparison with Experimental Data

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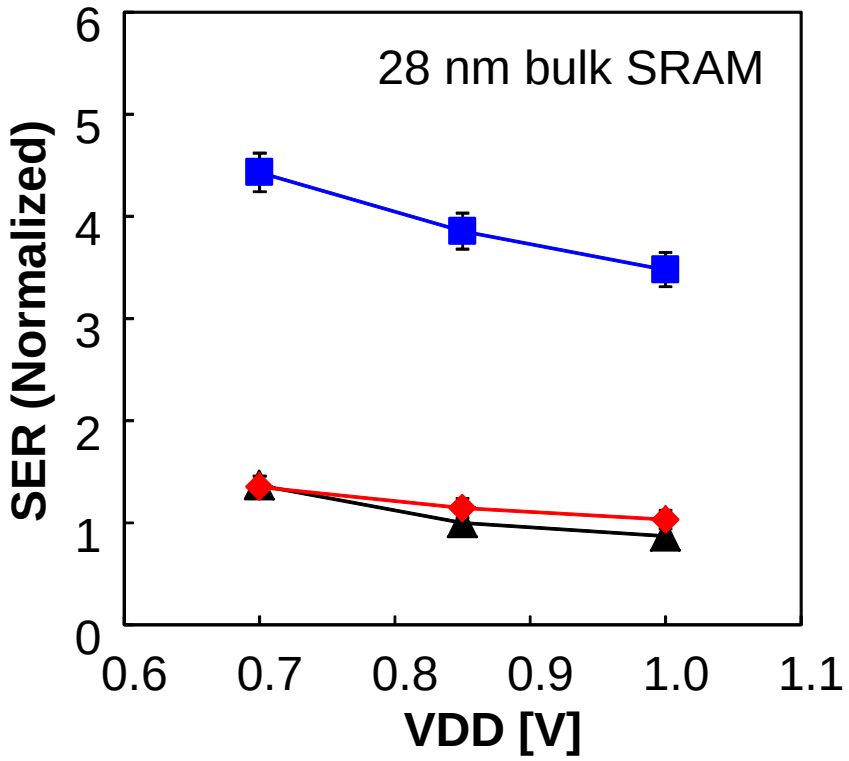
- SER of 28 nm bulk SRAM



PHYSERD (Q_{crit} method)

PHYSERD + Circuit Sim. (Waveform method)

Experiment at RCNP

RCNP: Research Center of Nuclear Physics (Osaka Univ., Japan)

- Waveform method shows an excellent agreement with experiment.
- Q_{crit} method overestimates SER by 4 times.

➢ **Our waveform method is an appropriate approach.**

Why does Q_{crit} method overestimate?

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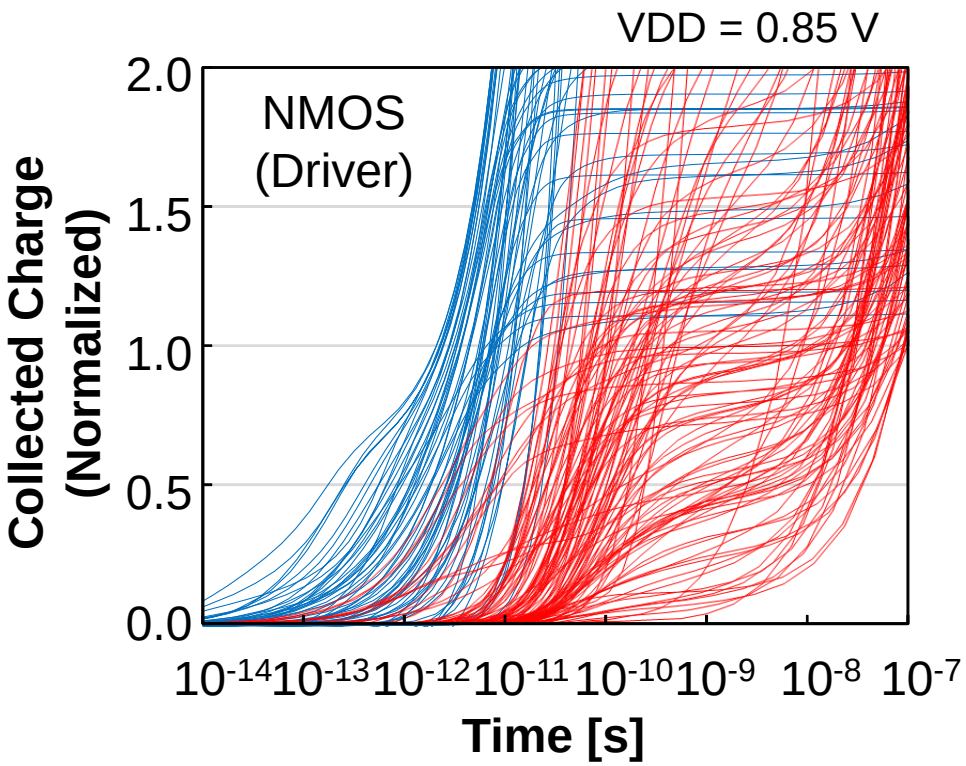
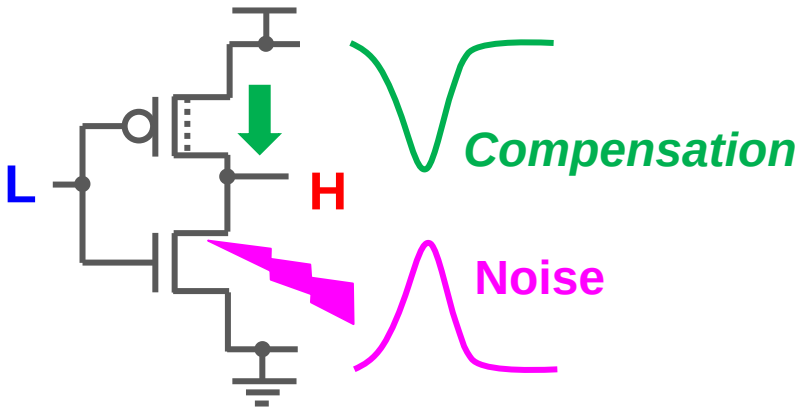
- Charge collection waveforms of SEU events



Self-compensation



Slow perturbations can be compensated effectively.

✓ **Q_{crit} method does not include self-compensation.**

Blue lines: Q_{crit} and waveform methods

Red lines: Q_{crit} method **= OVERESTIMATION**

Contribution of Transistors

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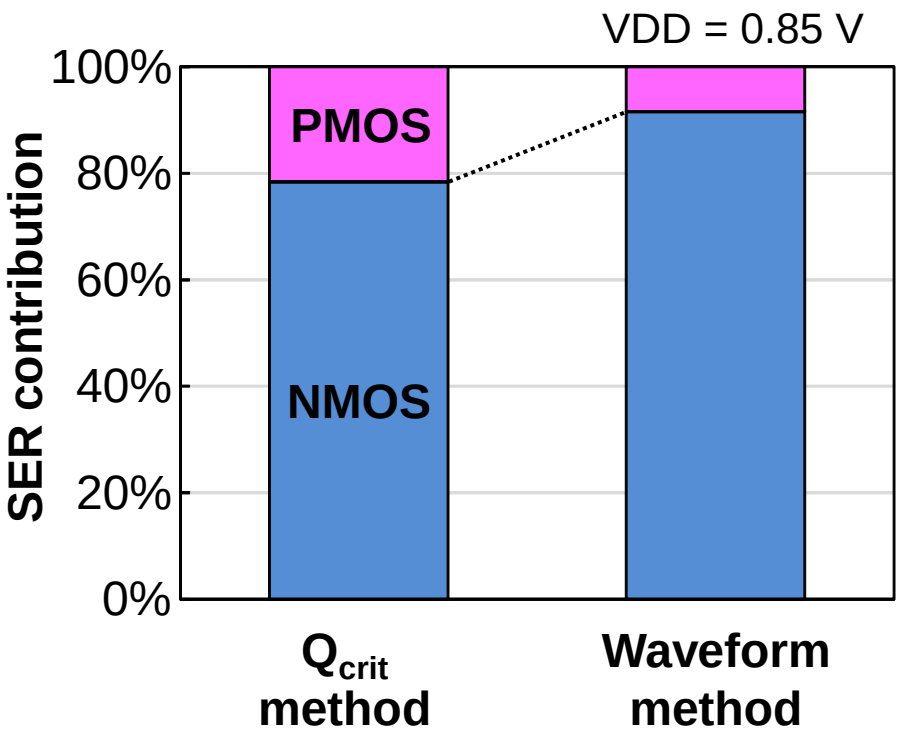
- NMOS (Driver) and PMOS (Load)



Factors determining contribution

Sensitive area	**NMOS > PMOS**
Q_{crit}	**NMOS < PMOS**
Self-compensation	**NMOS < PMOS**

Higher driving power of NMOS
→ More compensation in PMOS

✓ **is not included in Q_{crit} method**

- NMOS shows a dominant contribution to SER.
- Q_{crit} method estimates a higher contribution of PMOS.

➢ **Our waveform method can analyze sensitive node properly.**

Contribution of Secondary Ions

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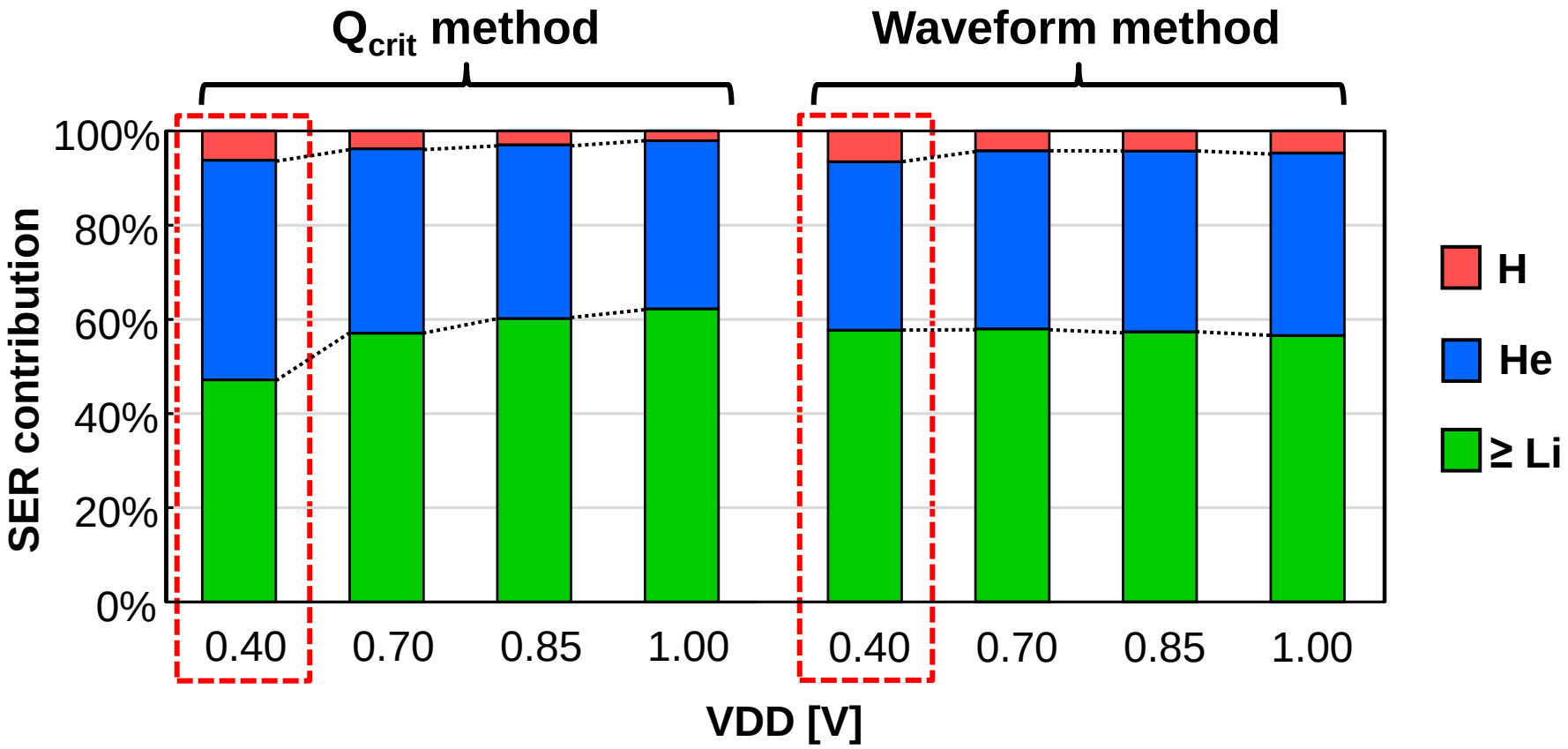
- proton (H), α-particle (He) and heavy ions (≥ Li)



- Each method shows different percentage, especially in low VDD.

➢ **Our waveform method is a good approach for analyzing species.**

More Comparison with Experimental Data

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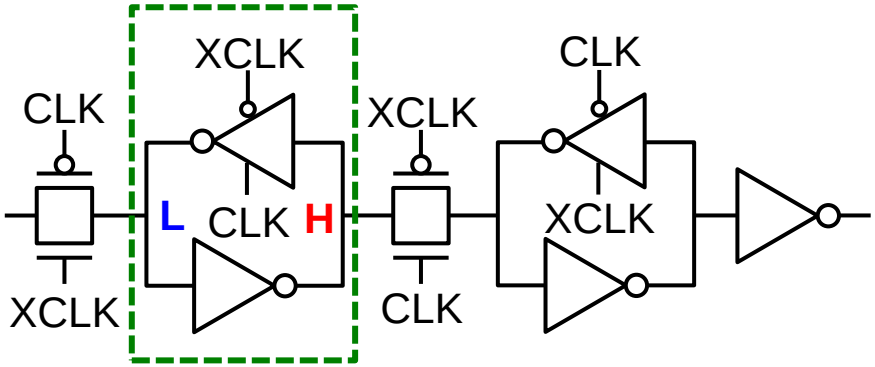
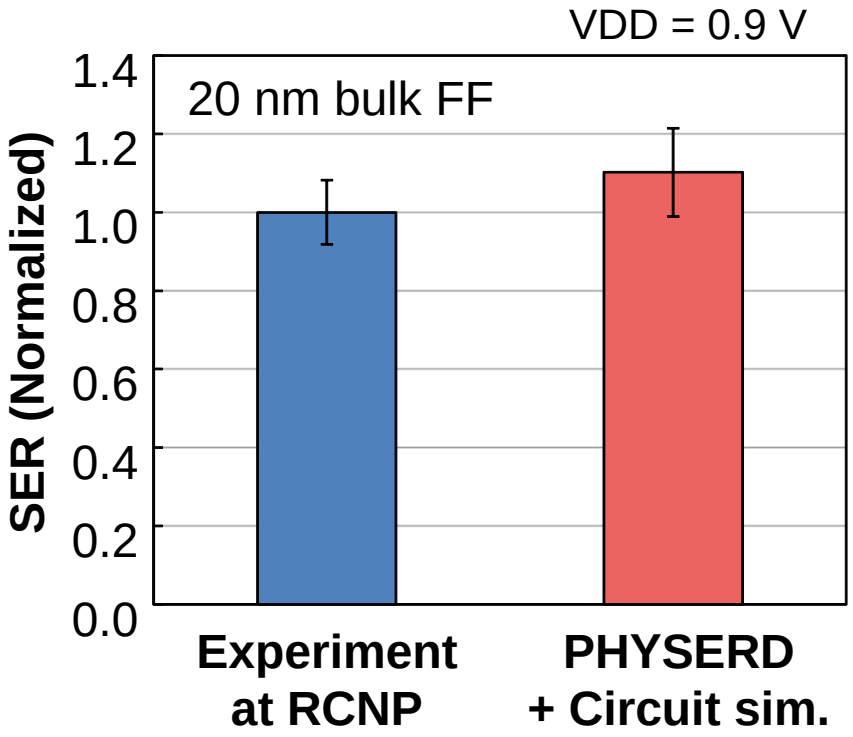
- SER of 20 nm bulk Flip-Flop

Schematic



CLK = High
→ *Master latch is sensitive to SEU.*



- PHYSERD + Circuit sim. shows a good agreement with experiment.
- But more verifications are needed to ensure this agreement.

➢ **Our simulation is probably applicable for sequential elements.**

Summary

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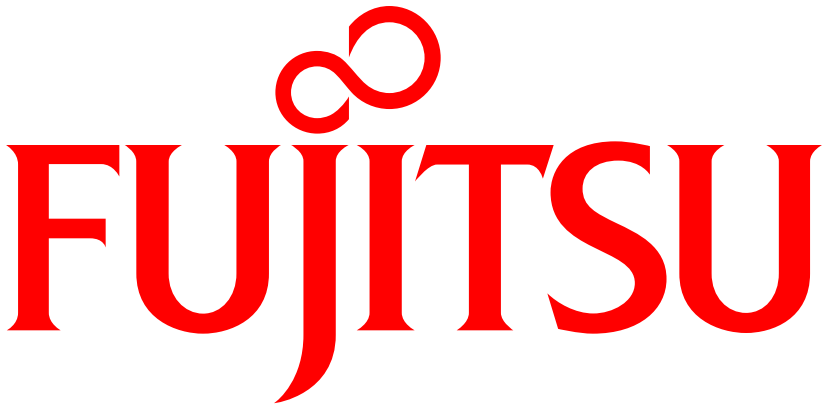
- We presented the accuracy verifications of PHYSERD and that with circuit simulation.
- PHYSERD + circuit simulation showed an excellent agreement with experimental data.
- Considering waveforms is essential for quantitative estimation of SER.
- We concluded that PHYSERD + circuit simulation is a useful approach to SER prediction.



shaping tomorrow with you