# Impact of Package on Neutron Induced Single Event Upset in 20 nm SRAM

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***Abstract*—This work investigates the impact of package structure on single event upset (SEU) rate through neutron irradiation test and Monte Carlo simulation of the particles passage. Irradiation test results show that the resin existing in the upper stream of the beam could increase SEU rate by about 10 %. The simulation result demonstrates that light secondary particles generated in the package materials, such as proton and alpha particles, contribute to the SEU rate elevation. Therefore, SEU rate evaluation should pay attention to the package structure especially for low voltage devices having low critical charge of 0.4 fC and below.**

***Keywords- Neutron irradiation test, Single event upset (SEU), SRAM, Package, Resin.***

## I. INTRODUCTION

Irradiation tests with spallation neutron sources have been widely performed for evaluating single event upset (SEU) in electronic devices. Generally, device under test (DUT) for the irradiation test is assembled with a particular package. On the other hand, when the devices are shipped as products, various kinds of packages are used for assembly depending on the cost and field environment. The package difference between the irradiated DUTs and actual products is not considered in the evaluation of terrestrial neutron induced SEU rate [1] although it has been considered in proton irradiation test for space application [2]. In addition, the impact of package was not explicitly evaluated in SEU rate simulation (e.g. [3]). On the other hand, secondary protons generated by nuclear reaction start to cause SEU in recent devices, especially in low voltage devices [4]. Such secondary protons can travel 10 to 1000 um, and hence the protons which are generated outside the die can reach transistors on the die and cause upsets.

In this work, we investigate SEU rate variation of a 20 nm SRAM due to package structure undergoing neutron irradiation tests, and Monte Carlo simulation with particle and heavy ion transport code system (PHITS) [5]. Our evaluation results point out that the measured SEU rate depends on the package structure and this SEU rate variation will be more significant for low voltage devices having low critical charge (Qcrit) of 0.4 fC and below.

## II. NEUTRON IRRADIATION TEST AND SIMULATION SETUP

We performed neutron irradiation test and simulation of the particles passage. Table I summaries DUTs and conditions of the irradiation test and the simulation. We used two DUTs in the irradiation test and three DUTs in the simulation. In the irradiation test, the DUT was irradiated from back end of line (BEOL) side or substrate side.

The neutron irradiation test was performed on the DUT that included 80 Mbit SRAM manufactured in 20 nm bulk CMOS technology. The test dies in this test were picked up from a single wafer. We used the spallation (broad spectrum) neutron beam at research center for nuclear physics (RCNP) of Osaka University. The average flux of neutrons whose energy was higher than 10 MeV was about 2 billion neutron/hour/cm$^2$. Figure 1 illustrates the DUT setup. One DUT on a test board was placed on the beam track. The SRAM die was assembled with a plastic package with wire bonding. Figure 2 shows the sizes of the package and die. To evaluate the impact of package structure on SEU rate, we prepared two types of package for the irradiation test; "Packaged" DUT is assembled with an ordinary package, and "De-capped" DUT is assembled with a package whose resin on the BEOL surface of the die is removed. Packaged and De-capped DUTs were irradiated from the BEOL side as shown in Figure 1(a). Additionally Packaged DUT was irradiated from the substrate side as shown in Figure 1(b).

Table I Combinations of DUT and irradiation condition.

| DUT name | Packaged | Packaged | De-capped | No-packaged |
|---|---|---|---|---|
| Packaged | Yes | Yes | Yes | No |
| De-capped | No | No | Yes | - |
| Irradiation face | BEOL side | Substrate side | BEOL side | BEOL side |
| Irradiation test | ✔ | ✔ | ✔ | |
| Simulation1 | ✔ | | ✔ | ✔ |
| Simulation2 | ✔ | | ✔ | |
| Simulation3 | ✔ | | ✔ | |

Table II Sensitive volume size assumed in the simulation.

| | Volume size |
|---|---|
| Simulation1 | 40 |
| Simulation2 | 3 |
| Simulation3 | 1 (Normalized) |

We calculated SEU cross sections to evaluate the impact of package structure. The calculation was carried out by Monte Carlo simulation using PHITS [5] with the sensitive volume method [4][6]. The three-dimensional DUT structure shown in Figure 3 was given to PHITS. Here, the given structure includes the package, lead frame, metal, silicon and polyimide layers, and sensitive volumes of SRAM bit cells. The three sizes of the sensitive volume in Table II were assumed in this simulation. The sensitive volume in Simulation3 corresponds with the NMOS drain size of the 20 nm SRAM under the irradiation test. The actual sensitive volume is larger than that in Simulation3 since the generated charge is collected to the drain through drift and diffusion. The socket and PCB board were not included. For a comparison, we prepared three DUT structures; "Packaged", "De-caped" and "No-package" in Figure 3 (B), (C) and (D), respectively. We calculated SEU cross section as a function of Qcrit, which is the minimum charge for SEU occurrence. Neutrons were injected from the BEOL side with normal incident angle in this simulation.

## III. Neutron Irradiation Test Result

Figure 3 shows the measured SEU rates of the 20 nm SRAM in three Packaged DUTs and three De-capped DUTs irradiated from BEOL side, and three Packaged DUTs irradiated from substrate side. The SEU rates in Figure 2 are the average in the three DUTs.

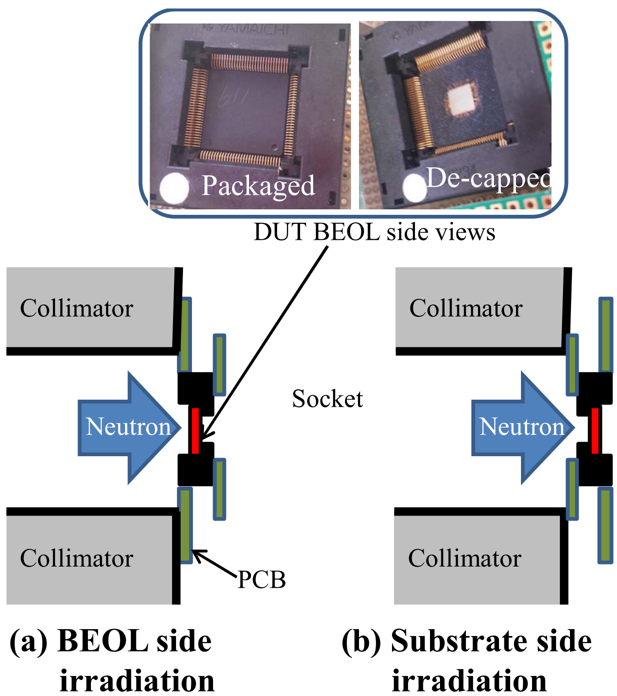


Figure 1. Setup of (a) BEOL side and (b) substrate side neutron irradiations to Packaged and De-capped DUTs.

For the irradiation from BEOL side, the SEU rate of Packaged DUT is about 10% higher than the SEU rate of De-capped DUT. This result indicates that the secondary ions generated inside the package resin reached the SRAM transistors and caused upsets. On the other hand, the SEU rate for the substrate side irradiation is about 20% lower than the SEU rate for the BEOL side irradiation. This result means that the package is an important factor determining the SEU rate and we need to pay attention to the impact of package and irradiation side[1] when selecting another package for actual products. The mechanism of the SEU rate variation will be discussed with simulation in the next section.

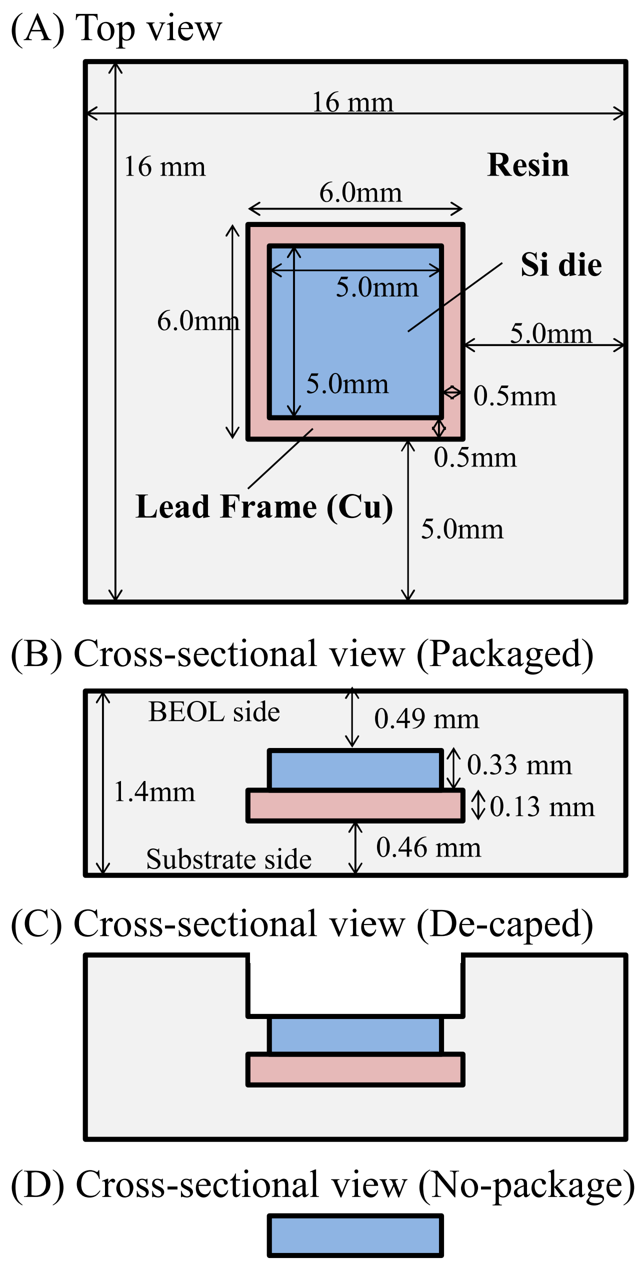


Figure 2. Package structure of the DUTs used in the neutron irradiation test and the simulation.

## IV. Simulation Result

Figure 4 shows the SEU cross sections calculated in Simulation1. Here, the cross sections are separately presented for proton, alpha particles and heavier ions. Simulation with large sensitive volume is suitable for estimating the contribution of each secondary particle to SEU rate in a shorter simulation time.

[1] For actual products, the irradiation side corresponds to the die surface which faces to the sky.

Comparing the cross sections of Packaged and De-capped DUTs, the package structure, i.e. the existence of resin on the die clearly differentiated the cross section. The de-capped package decreased the SEU cross sections for proton, alpha particles and heavy ions, which is consistent with the measurement result in Figure 3. Especially, the SEU cross sections for light particles, i.e. proton and alpha particles, were decreased significantly by de-capping. The protons and alpha particles which were generated outside the die contributed to the increase in the cross section. On the other hand, the cross section for the heavy ions less depended on the package resin existence since their travel distance is shorter than those of the light particles. Few heavy ions generated outside the die reached the sensitive volumes.

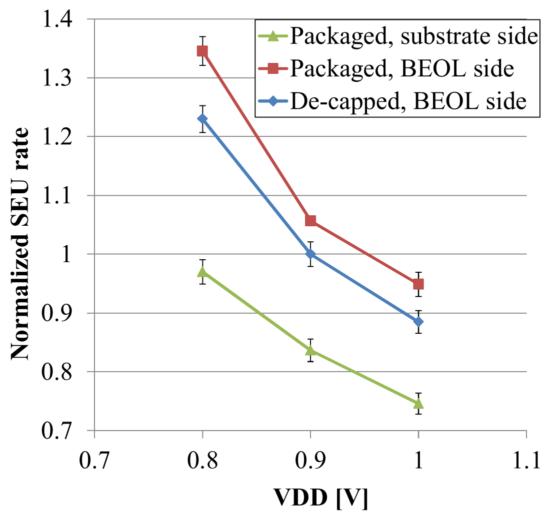


Figure 3. Measured SEU rates of Packaged DUTs irradiated from BEOL and substrate sides, and De-capped DUT irradiated from BEOL side. The SEU rates are normalized by the SEU rate of De-capped DUT at 0.9 V.

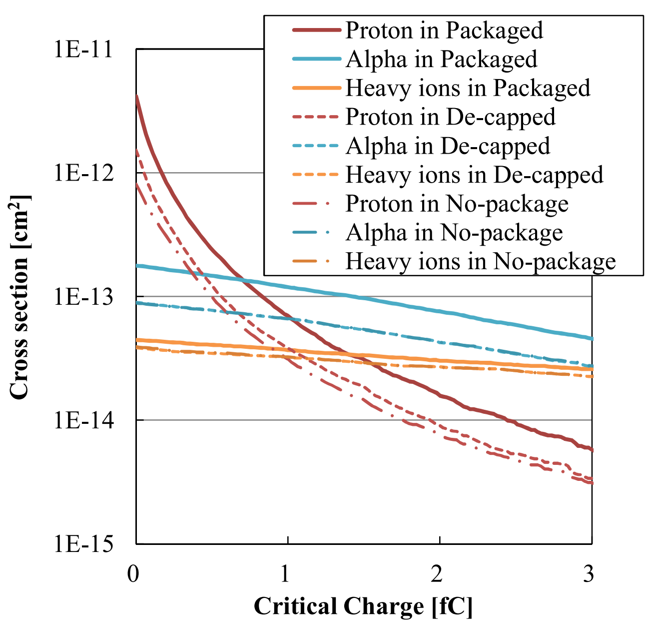


Figure 4. Calculated SEU cross sections for each secondary ion in Simulation1.

Figure 5 shows the ratios of the cross sections in Packaged DUT to those in De-capped DUT. In all the range of Qcrit, the ratios of proton and alpha particles are higher than that of heavy ions. This is reasonable since protons and alpha particles generated in the package can reach the SRAM transistors, as discussed above. An interesting observation is that the ratio of proton increases rapidly below 0.4 fC. Note that Qcrit of the 20 nm SRAM at 0.9V is larger than 0.4 fC. This observation leads us to anticipate that we would see this rapid increase when characterizing the SRAM SEU rate at lower voltage operation. In fact, the simulation that did not include the package structure in [4] underestimated the SEU rate of 90 nm SRAM at 0.19V operation to 1/100. Our work in this paper suggests that one of the major reasons for this underestimation is the ignorance of the particles generated in the package.

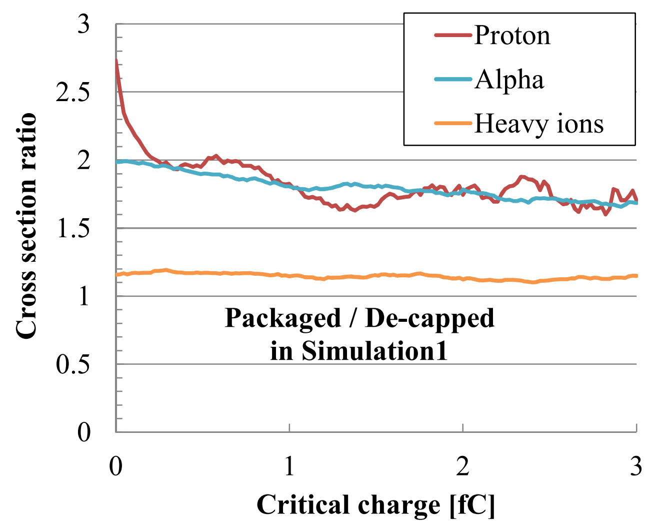


Figure 5. Calcurated SEU cross section ratios for secondaly proton, alpha particles and heavy ions in Simulation1. The ratio is defined as the SEU cross section of Pckaged divided by the SEU cross section of De-capped.

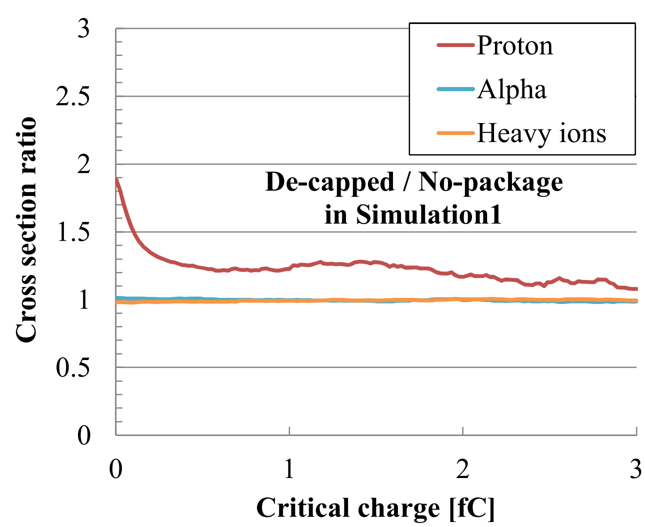


Figure 6. Calculated SEU cross section ratios for secondaly proton, alpha particles and heavy ions in Simulation1. The ratio is defined as the SEU cross section of De-capped divided by the SEU cross section of No-package.

Next, the SEU cross sections of De-capped and No-package DUTs are compared. For making the comparison easier, Figure 6 shows the ratio of SEU cross sections of De-capped DUT divided by those of No-package DUT. The cross section ratios for alpha particles and heavy ions are very close to 1. This is because alpha particles and heavy ions generated in the resin on the substrate side cannot travel across the silicon substrate (330 um) and reach the transistors. On the other hand, the ratio for proton is higher than 1. This means that the protons generated in the resin on the substrate surface can travel across the silicon substrate and contribute to SEU occurrence.

We also evaluated the cross section ratio for different sizes of sensitive volume. Figure 7 shows the ratio of cross section of Packaged DUT to that of De-capped DUT in Simulation1, 2 and 3. The sensitive volume size decreases in the order of Simulation1, 2 and 3 as shown in Table II. As the sensitive volume becomes smaller, alpha particle and proton are less likely to deposit charge large enough to cause upsets [6].

The decrease in the cross section due to de-capping was about 10 % in the irradiation test. On the other hand, in the simulation, the decrease is more than 50 % at the critical charge of 0.6 fC and below in all the simulations. One of the possible reasons of this overestimation is that the simulation did not consider the secondary ions generated outside the package. For taking into account the effect of such secondary ions, a larger structure which includes socket and PCB needs to be given to PHITS [5]. Another possible reason is that this simulation is based on the sensitive volume method and it did not explicitly consider the phenomena unique to bulk transistors such as parasitic bipolar action. Although PHYSERD simulation [7], which combines PHITS and a device simulator, can reproduce such device phenomena, the simulation time is prohibitively long. For more accurate evaluation of the package effect, PHYSED or other similar simulation methodology needs to be drastically accelerated.

## V. CONCLUSIONS

We investigated the impact of package on SEU evaluation through neutron irradiation test and simulation. The measurement results showed that the package structure affected the SEU rate. This package effect should be considered when we select a package different from the package used in the irradiation test for actual products. The simulation results demonstrated that the package effect originated from light secondary ions such as proton and alpha particles. We also pointed out that the package effect would be more significant for the devices having Qcrit below 0.4 fC.

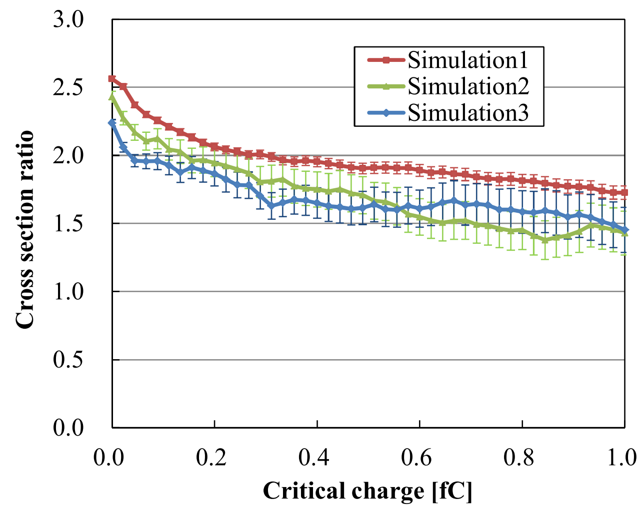


Figure 7. Calcurated SEU cross section ratio for all secondaly particles. The ratio is defined as the SEU cross section of Packaged DUT divided by the SEU cross section of De-capped DUT.

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