Assessing alpha-particle-induced SEU sensitivity of flip-chip bonded SRAM using high energy irradiation

Saqib A. Khan1a), Shi-Jie Wen2, and Sanghyeong Baeg1
1 Department of Elec. & Comm. Engineering, Hanyang University, ERICA Campus, 55 Hanyangdaehak-ro, Sangnoksu-gu, Gyeonggi-do, 426–791, Korea
2 Component Engineering Group, Cisco System Inc., San Jose, CA 95134, USA
a) saqibkhan@hanyang.ac.kr

Abstract: The contribution of alpha particles to soft error rate is quite significant, especially in planar CMOS technology. Due to high packaging density and heat dissipation mitigation technique, microelectronic devices are packaged upside down, which precludes their testing against alpha particles. The ions emitted by alpha isotopes can penetrate neither package nor substrate, from top or backside of the device, respectively, to induce upsets. This paper assesses SRAM single-event upset (SEU) sensitivity against alpha particles using high energies, irradiated from the backside of substrate. The SEU cross-section is measured at alpha various LETs (Linear Energy Transfer) values at the sensitive volume—including the Bragg’s peak, for which the sensitivity is maximum. In addition, some insights into high energy alpha backside irradiation are also discussed.

Keywords: alpha particle, soft errors, single event upset (SEU), GEANT4

Classification: Integrated circuits

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1 Introduction

At ground level, alpha particle is a significant contributor to soft error rate (SER) of a memory device [1]. SRAM is the most susceptible electronic device to the ionization radiation. To reduce its vulnerability against radiation, many radiation-hardened and tolerant memory cells’ designs have been proposed, like [2, 3]. Advanced memory devices are packaged upside down to achieve high-density packaging and for heat dissipation mitigation. Single event effect (SEE) testing of such microelectronics devices is a huge challenge [4]. Alpha particles, emitted by radioactive isotopes, have very short range which prevents their penetration till the active circuit to deposit charge to induce upsets during SEE tests. As a result, part of chip and package is chemically etched away to allow particle to transport till sensitive node. On the contrary, other radiation sources, i.e. neutron and proton, have very long penetration depth inside target materials which allow a device be tested from either side—in any type of packaging [5, 6]. The device sensitivity against heavy-ions in a close package has been evaluated using long range, high energy heavy-ions along with energy degraders to measure cross-section [7]. High energy alpha particles have also been shown to penetrate the thick substrate from backside to induce upsets in an SRAM device [8].

In this paper, we evaluate a flip-chip packaged memory device single event upset (SEU) sensitivity against alpha particle from the backside of its substrate using a range of alpha high energies. The irradiated ions penetrate entire silicon (Si) substrate before depositing charge in the sensitive volume (SV) of device. The SEU cross-section is measured at alpha various Linear Energy Transfer (LET) values, including the Bragg’s peak which gives highest sensitivity, using a range high energies. The charge deposition in Si substrate for backside irradiations is also analyzed using tests and Monte Carlo simulations. Experiments were performed on a high-density, flip-chip bonded commercial SRAM device, fabricated in 55-nm bulk CMOS technology. Test and Monte-Carlo based simulation results are presented. In addition, few insights into high energy alpha backside irradiation are also discussed.
2 Monte-Carlo simulations

2.1 SRIM/TRIM simulation

For high energy alpha backside irradiation, incident particles have to penetrate and traverse the entire Si substrate before depositing charge in the device’s SV; active circuit lies beneath the substrate. For thicker substrate, higher energy is required by an incident ion to penetrate to reach the active circuit of device. The range of alpha ion in Si for various energies is calculated using SRIM [9], and is shown in Fig. 1(a). For high energy alpha backside irradiation, the LET of an alpha particle at SV is not same as device surface because the distance from the die surface to SV is huge, unlike front-side testing in a wire-bonded device. Fig. 1(a) also shows alpha initial LET, which is the LET at die surface. To determine charge deposition by high energy alpha particle inside substrate, its interaction with Si is simulated using TRIM [9]. It also determines the LET at SV inside Si for specific incident energy and substrate thickness. Fig. 1(b) shows alpha LET as a function of Si substrate thickness for various high energies. The LET is highest close to the end of its path inside Si substrate for all alpha energy values; this point is referred to as Bragg’s peak. The charge deposition is highest at the Bragg’s peak due to maximum ionization. At even higher energies, LET at the active circuit decreases with the increase in incident energy. Therefore the LET at SV may be varied by increasing incident energy to measure SEU cross-section at various LETs.

![Fig. 1. (a) The range and LET of an alpha ion in silicon (b) The LET of an alpha ion as a function of distance in silicon (substrate thickness)](image)

2.2 CRÈME simulation

CRÈME-MC is a GEANT4 based Monte-Carlo predictive tool [10], which quantifies the energy deposited by ionization radiation in the physical model of micro-electronic devices. It is used to determine the statistical profile of energy deposition events inside SV for high energy alpha particles irradiation — from the backside of Si bulk. Sensitive volume of a device is the region where charge disposition, exceeding critical charge, by ionizing radiation, cause a bit upset. The critical charge is the minimum charge required to be collected by the sensitive node to experience an upset.
The device is modeled as a rectangular structure, composed of Si, with suitable lateral dimensions. The height of Si bulk structure represents the thickness of Si die, which is determined from test data and TRIM simulations together. The SV is placed at the bottom of Si bulk and is irradiated from other side to signify backside testing. The irradiated particles are distributed randomly and strike the device surface perpendicularly. The SV is the drain region whose dimensions are consistent with the similar technologies [11, 12]. The SEU cross-section of the device is calculated using traditional rectangular parallelepiped models [13], which does not account for the charge collection due to diffusion of carriers from longer distance with respect to sensitive node. The particles which do not directly strike the drain region would not cause any upsets due to diffusion of charges alone. Fig. 2 shows simulation cross-section at alpha various high energies, irradiated from the backside of substrate. The critical charge of about 1.4 fC fits well with the experimental data which is in close agreement with the actual value.

3 High energy alpha experimental results

High energy alpha experiments were performed at Korea Institute of Radiological & Medical Sciences (KIRAMS), Korea. The facility provides more or less a mono-energetic alpha beam. The particles emerging from the beam have long enough range to penetrate Si substrate of any thickness. The air may be used as energy degrader, by placing the device-under-test (DUT) at various positions relative to beam, to obtain a range of incident energies. The device evaluated in this paper is 55-nm 6T SRAM - assemble in a flip-chip structure. It was written with a known data pattern prior to irradiation. All the tests were performed in dynamic mode at normal voltage and at room temperature. The particles emerging from beam strike perpendicularly at the DUT. The irradiated energies have sufficient penetration depth to pass through the entire substrate to reach active circuit and induce upsets. The particle flux was varying at each incident energy value; it was large enough to produce statistically an adequate number of errors. The number of upsets was...
recorded at each energy value and the cross-section was measured. The bitmap plot at various energies is shown in Fig. 3, where each plot shows the location of upset.

![Bitmap plots at various alpha energies](image)

**Fig. 3.** Memory bit map plots at various alpha energies; the fluence is not same at each incident energy: (a) 30 MeV (b) 31 MeV (c) 33 MeV (d) 35 MeV (e) 36 MeV (f) 38 MeV

### 4 Discussion

High energy alpha induced test cross-section increases sharply at a particular energy, followed by sudden drop; it becomes rather constant at higher energies. The shape of Bragg’s peak is very sharp which causes the cross-section to increase and fall abruptly. The LET at SV is highest and so is the sensitivity because the charge deposited inside SV is a maximum at Bragg’s peak. Consequently, the measured cross-section, at energy corresponding to Bragg’ peak, is highest — so is the soft error rate. The bit map plot shows maximum number of upsets at 31 MeV. The cross-section does not changes much at higher energy due to the fact that LET at the SV becomes also constant. Therefore, high energy alpha irradiation gives the device minimum and maximum alpha SER. The SEE test results are consistent with simulation cross-section, as shown in Fig. 4.

![Simulation and experimental cross-section](image)

**Fig. 4.** Test and simulation cross-section at alpha various energies; It is normalized with test cross-section at 31 MeV
It is noted that the shape of alpha LET curve as a function of Si substrate thickness remains unchanged, irrespective of incident energy. Moreover, it is also observed that high energy alpha particle loses energy towards the end of its track in the same way as does low energy particle, as shown in Fig. 5. Alpha isotope emits energy about 5.3 MeV or 5.5 MeV. This means that high energy irradiation may be used to mimic low energy alpha particles at the active circuit from the backside of substrate. It would allow flip-chip packaged devices to be tested against alpha particles of same energy as emitted by isotopes to calculate their SER.

The substrate thickness of the device is measured using test data. The VDBG method has been used to measure the depth of active circuit beneath the closed package from the topside [7]. The same method is used to measure the substrate thickness using high energy alpha irradiation from the backside. The sensitivity of the device was found to be higher for backside than front-side for proton and Uranium ions in [14]. Moreover, it was deduced that proton and Uranium ions triggered higher charge deposition event due to secondary particles that were produced as a result of nuclear reactions between the incident ions and atoms of Si substrate. However, the device sensitivity for high energy alpha, irradiated from the backside of substrate, does not change. Alpha particle is not likely to have nuclear reaction with the atoms of target material—it interacts in electronic way.

5 Conclusion

The SEU cross-section for SRAM is determined at various LET values, which gives the flip-chip device lowest and highest alpha-induced soft error rate (SER). The device is tested from backside without having to etch away its substrate or part of package/chip. The sensitivity of the device doesn’t change in case of high energy alpha backside irradiation. The simulation results are consistent with high energy alpha experimental data.

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