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Technology Trend of Soft Errors based on Accurate Estimation Method

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1. Introduction

The soft error (SE) has become a serious problem in VLSI [1]. The sources of SEs are high-energy neutrons, thermal neutrons, and α-particles (Fig. 1). High-E neutrons and thermal neutrons are the secondary cosmic ray and they induce SEs through neutron-nucleus reactions in the silicon substrate and thermal neutron capture reactions of ^{10}B in BPSG (borophospho-silicate glass), respectively. Because the CMP process is used in place of BPSG in recent CMOS technologies, we can ignore the effect of thermal neutrons in most cases. Therefore, accurate estimations of high-E neutron- and α-induced soft error rates (SERs) are essential. However, the magnitude relation between neutron- and α-SERs has long been unclear. Recently, we developed a sensitive dosimetry, vacuum α-tracking (VAT) method [2], to measure dose rates of α-particle emission and showed that the detection limit of the developed dosimetry is 30 times more sensitive than that of conventional dosimetry. Thus, the VAT method enables us to eliminate the ambiguity in SER estimations.

In this paper, we investigated the technology trend of SERs in advanced CMOS circuits by using neutron- and α-accelerated tests and SER simulations. The newly obtained dose rates of α-particle emission enabled us to estimate α-particle-induced SERs accurately. An advanced neutron white beam was recently developed at Research Center for Nuclear Physics (RCNP) of Osaka University [3]. We used this neutron beam for neutron accelerated tests.

2. SER Estimation Method

We carried out high-energy neutron- and α-accelerated tests on 90/130-nm SRAMs and 90-nm latch circuit. An advanced neutron white beam, which was recently developed for SE investigations at RCNP, was used for high energy neutron-accelerated tests. It is similar to that of LANSCE (Los Alamos Neutron Science Center) and has an energy spectrum similar to that of sea-level atmospheric neutrons (Fig. 2). Accelerated neutron-SERs were normalized by a neutron intensity of 14 nph·cm^{-2} (E_n > 10 MeV, New York) [4]. α-accelerated tests were also performed using ^{241}Am. In this paper, we also used our simulator NISES-II [5] for neutron- and α-SER simulations.

Dose rates of α-particle emission from LSI materials measured with the VAT method are listed in Table 1. In VAT method, its sensitivity is remarkably improved by exposing the detector plate to α-particles from sample material in vacuum chamber as a result of lowered background radiation. The detection limit of the VAT method proved to be 3.2×10^{-5} αph·cm^{-2} [2] (αph represents 'α-particles per hour'). On the other hand, a gas flow proportional counter with a detection limit of 1×10^{-3} αph·cm^{-2} has been widely used to measure the α-dose rates until now. Thus, we had to use the detection limit value of 1×10^{-3} αph·cm^{-2} for materials with actual α-dose rates lower than the detection limit value to estimate α-SERs and this yielded overestimations of α-SERs. As seen in Table 1, dose rates of these materials are lower than the detection limit of a gas flow proportional counter. We used these new values for α-SER estimations.

3. Results and Discussion

Simulated α-SERs for a 130-nm SRAM based on the newly obtained dose rates (Table 1) are shown in Fig. 3. Old data based on the detection limit value of 1×10^{-3} αph·cm^{-2} are also shown. Using the newly obtained dose rates reduces the α-SERs remarkably. Figure 4 compares α-SERs with neutron-SERs in the 130-nm SRAM. Figure 4 suggests that if we do not use solder bump in SRAMs, α-SERs are negligible in comparison with neutron-SERs. Under normal operation at Vdd = 1.2V, a ratio of [α-SER(Metal)]/[neutron-SER] ≈ 0.06, which is consistent with measured ratio (≈ 0.04) in ref. [6]. Figure 5 shows simulated and measured accelerated SERs. We normalized accelerated α-SERs by 2.2×10^{-4} αph·cm^{-2} (Table 1, Low-α SnAg solder type II). NISES-II reproduced measured accelerated α- and neutron-SERs with a margin for error of 20-40%. Accelerated α-SERs measured by using ^{241}Am are very similar to those due to α-particles emitted from solder bump (Fig. 5). Hereafter, we normalize accelerated α-SERs by the dose rate of 2.2×10^{-4} αph·cm^{-2}.

Figure 6 shows the technology trend of SERs in SRAMs. Accelerated and simulated SERs for each technology node are shown. Although the SER in SRAMs for single cells has stayed almost constant in recent technologies, it has decreased slightly as the technology advanced. High-E neutrons dominated in the total SERs, while the contribution of α-particles was rather small.

Figure 7 shows the process dependence on neutron- and α-SERs in 90-nm latch circuits which include low leak (LL), high speed (HS), ultra-high speed (UHS) transistors (Ion (UHS) > Ion(HS) > Ion(LL)), with twin and triple well (2well and 3well) dopant profiles. Differences in neutron-SERs are less than 50%. However, α-SERs for triple-well LL latches are 1/2 - 1/10 of those for 2well LL latches in all "0" case. Furthermore, α-SERs for 2well HS and UHS latches are 1/2 - 1/3 of those for 2well LL latches. From these results, when α-SER decreases rapidly as the supply voltage (or the critical charge) increases, the process difference strongly affects SERs. However, because neutron-SERs are greater than α-SERs, the process effects on total SER (neutron-SER + α-SER) are small.

Although SERs are dominated by neutrons in many cases, α-SERs are not always small. For example, figure 8 shows simulated SERs in 90/130-nm SRAMs with bump type 1; low-α SnAg solder bump with the dose rate of 2.2×10^{-4} αph·cm^{-2}, type 2; low-α PbSn solder bump with the dose rate of 1×10^{-3} αph·cm^{-2}, and type 3; low-α PbSn solder bump with the dose rate of 1×10^{-2} αph·cm^{-2}. Effects of α-particles from Cu film (1.5×10^{-4} αph·cm^{-2}) and neutrons were also included in the simulations. The contribution of α-particles is similar to that of neutrons in the SER with bump type 2 and the contribution of α-particles is much larger than that of neutrons in the SER with bump type 3. This means that if we use materials with the dose rate of $>1\times10^{-3}$ αph·cm^{-2}, SERs are dominated by α-particles. In these cases, some countermeasures are needed to reduce the effects of α-particles. For example, we can reduce α-SERs by setting the material position apart from the device region.

4. Conclusion

The technology trend of SERs was investigated by using neutron- and α-accelerated tests and SER simulations. The newly obtained α-dose rates enabled us to estimate α-SERs accurately. The SER in SRAMs for single cells decreased slightly as the technology advanced. Although the process difference strongly affected on α-SERs in 90-nm latches, the process effects on total SER (neutron-SER +α-SER) were small. High-E neutrons dominated in the total SERs and the α-SERs are negligible in compared with neutron-SERs in many cases. However, if we use materials with the α-dose rate of $>1\times10^{-3}$ αph·cm^{-2} in SRAMs, SERs are dominated by α-particles.

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TABLE 1.

DOSE RATES OF α-PARTICLE EMISSION FROM LSI MATELIALDS

Material (thickness)	Dose rate of α-particle emission (αph·cm^{-2})
Electroplated Cu film (10 μm)	$1.5\times10^{-4}\pm2.6\times10^{-5}$
Low-α SnAg solder, type I (> 100 μm)	$5.6\times10^{-4}\pm3.0\times10^{-5}$
Low-α SnAg solder, type II (> 100 μm)	$2.2\times10^{-4}\pm2.8\times10^{-5}$

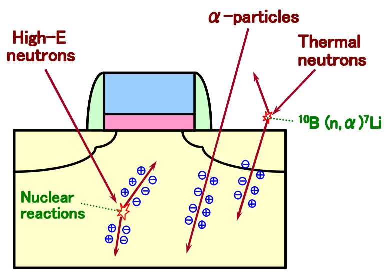

Fig. 1. Origins of soft errors.

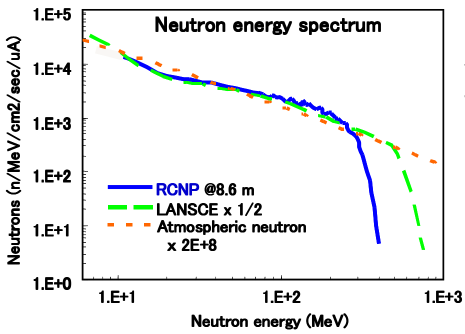

Fig. 2. Neutron energy spectrum of RCNP neutron white beam. Spectra of LANSCE neutron beam and of atmospheric neutrons are also shown.

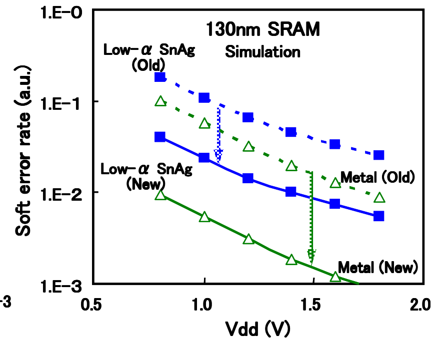

Fig. 3. Simulated SERs in 130 nm SRAM. 0.001αph·cm^{-2} was used for Low-α SnAg solder (Old) and Metal (Old). Dose rates in table 1 were used for Low-α SnAg solder type II (New) and Metal (New).

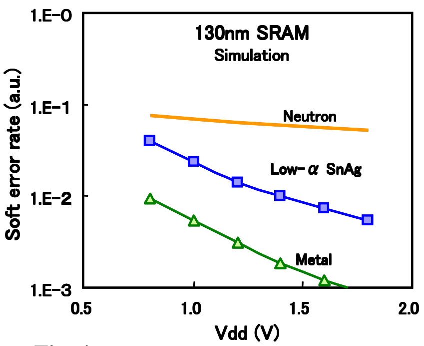

Fig. 4. Simulated neutron- and α-SERs in 130-nm SRAM. Dose rates in table 1 were used for Low-α SnAg solder type II and Metal.

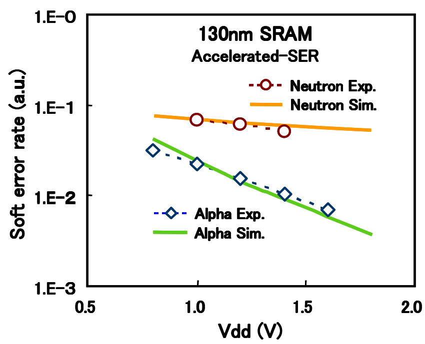

Fig. 5. Accelerated neutron- and α-SERs in 130- nm SRAM. Measured and simulated SERs are shown. Neutron- and α-SERs were normalized by 14 nph·cm^{-2} and 2.2 $\times10^{-4}$ αph·cm^{-2}.

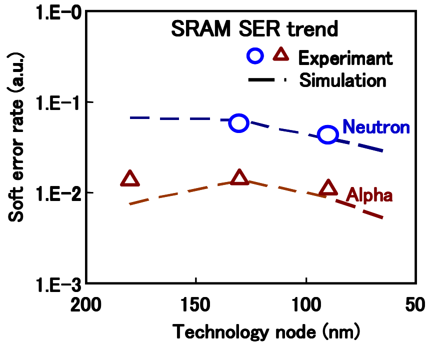

Fig. 6. Technology trend of SERs in SRAMs. Accelerated and simulated SERs caused by α-particles and high-E neutrons as are shown.

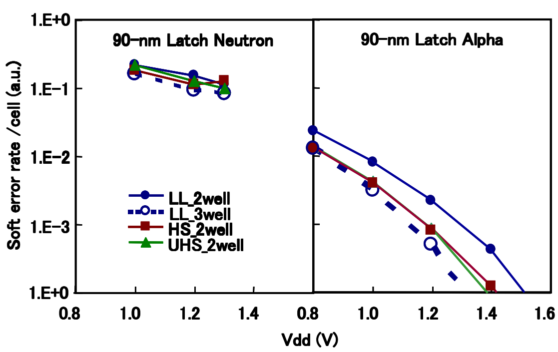

Fig. 7. Accelerated neutron- and α-SERs in 90- nm latch. Measured SERs are shown. Neutron- and α-SERs were normalized by 14 nph·cm^{-2} and 2.2 $\times10^{-4}$ αph·cm^{-2}.

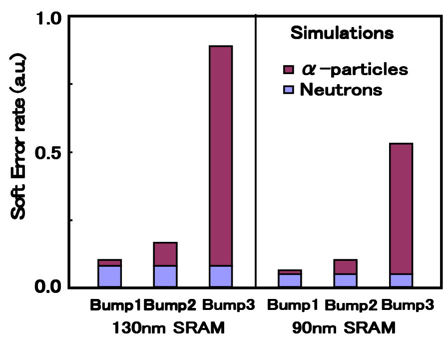

Fig. 8. Simulated SERs in 90/130-nm SRAM with bump1; Low-α SnAg solder with 2.2×10^{-4} αph·cm^{-2}, bump2; Low-α PbSn solder with 1×10^{-3} αph·cm^{-2}, and bump3; Low-α PbSn solder with 1×10^{-2} αph·cm^{-2}.