# Neutron-SER Modeling & Simulation for 0.18μm CMOS Technology

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**Abstract**

This paper presents a new and physical modeling approach for neutron SER with excellent accuracy demonstrated on SRAMs fabricated using 0.18μm CMOS technology. The SER contribution of each type of recoil ion and a fast roll-off behavior of neutron SER for high $Q_{CRIT}$ nodes are reported for the first time.

## 1 Introduction

Neutrons from terrestrial cosmic rays and alpha particles from radioactive impurities in packaging materials are the primary radiation sources that contribute to the soft-error rate (SER) of electronic products in non-space applications. [1-2] While the alpha particle contribution increases at a faster rate as processing technology scales to smaller feature sizes,[3] its impact can be minimized using advanced packaging techniques, such as low-emissivity solder materials. Neutron contributions, however, cannot be easily reduced due to the relatively fixed environment and will continue to dominate the logic circuit SER. In the past two decades, many experimental and theoretical studies have been performed to analyze neutron SER, but most of them have used the charge-burst model, which treats all recoil ions collectively, thus preventing detailed understanding of each recoil ion's contribution. [4-8] The charge-burst model also relies on experimental determination of charge collection efficiency, which could be more accurately analyzed using numerical 3D device simulations that provide superior predictability to future technology generations and enable S/D doping engineering for SER reduction.

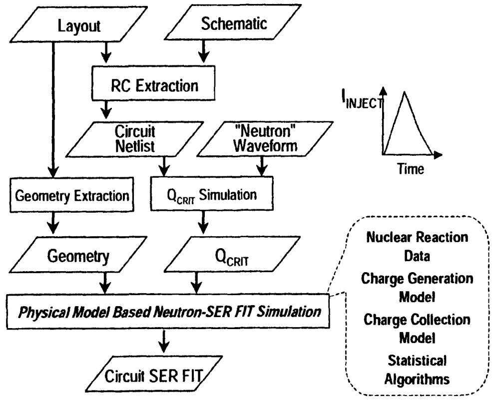



**Fig. 1.** Neutron-SER modeling and simulation methodology and flow

This paper presents a new and physical modeling and simulation approach for neutron SER, shown in Fig.1, including (1) neutron-silicon-nuclear-reaction-based recoil ion charge generation model, (2) numerical-device-simulation-based charge collection model, and (3) statistical algorithms for FIT (Failure-In-Time) rate simulation. We also present the simulated and experimental neutron-SER results of SRAMs fabricated using 0.18μm CMOS technology.[9] This paper for the first time reports the SER contribution of each type of recoil ion as well as the fast roll-off behavior of neutron-SER for high $Q_{CRIT}$ nodes. The physical models and simulation capabilities discussed in this paper have also been used to study the impact of CMOS process scaling and SOI on soft error rates of logic processes. [10]

## 2 Modeling and Simulation Methodology

$Q_{CRIT}$ for a given node is the critical amount of charge required for a given circuit to switch when a current pulse representing a recoil ion's charge is injected at that node. It is obtained via circuit simulations from the minimum pulse height that logically fails the circuit. Compared to alpha strikes, recoil ions typically have a much faster transient process, resulting in a sharper collection waveform and smaller $Q_{CRIT}$ because the circuit node has less time to respond. The neutron SER can then be calculated by computing the total probability of all recoil ions with a collected charge exceeding $Q_{CRIT}$.

## 3 Charge Generation and Collection Modeling

As an electrically neutral particle, a neutron can only interact with silicon nuclei through strong interaction, which can produce recoil ions with Zs ranging from 2 (He) to 15 (P). Fig. 2a shows the probabilities of each type of ion produced within a unit volume and time as a function of the recoil ion's kinetic energy. These probabilities are based upon the nuclear reaction cross-sections between monotonic neutrons and silicon nuclei and weighted by the sea-level neutron energy spectrum, as shown in Fig. 2b. [2, 11-12] Secondary neutrons and protons can also be produced, but are not included in the modeling because of their negligible contribution.

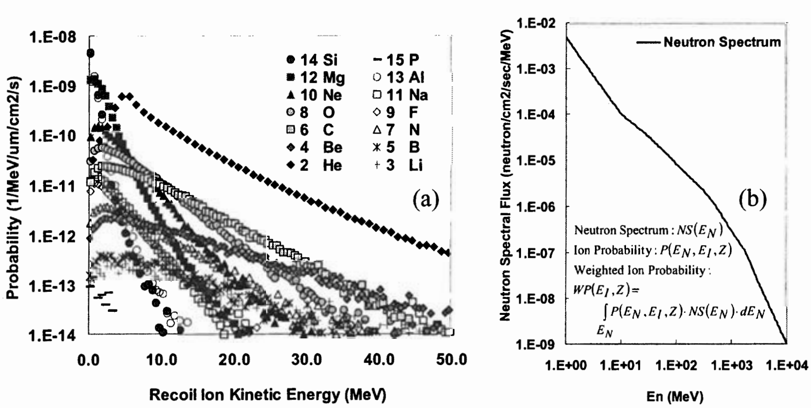



**Fig. 2.** (a) Energy transfer probability of recoil ions in neutron-silicon interaction, weighted by the sea level neutron spectrum; (b) Sea level neutron spectrum

The charge generation model is based on the ion energy loss rate in silicon (shown in Fig. 3) and the recoil path location relative to the S/D-to-well junction and trench isolations (shown in Fig. 4a).

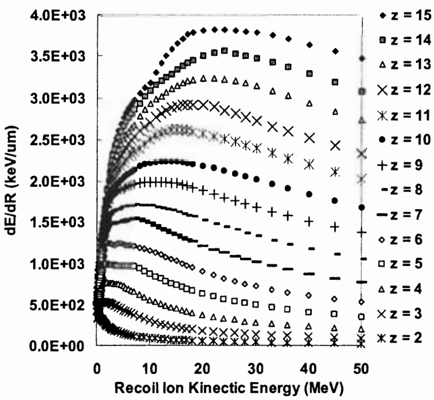



**Fig. 3.** Recoil ion energy loss rate in silicon, simulated using TRIM [13]

The charge collection model is obtained using Intel's proprietary numerical device simulator, by placing a point charge source at various locations near the S/D-to-well junction during the transient simulation and measuring the proportion of charge collected. As shown by Fig. 4b, the charge collection efficiency is near 1 inside depletion region and decreases almost linearly outside this region. By combining this collection efficiency with the charge generation function along the recoil path, the total charge collection can be obtained for a given recoil event.

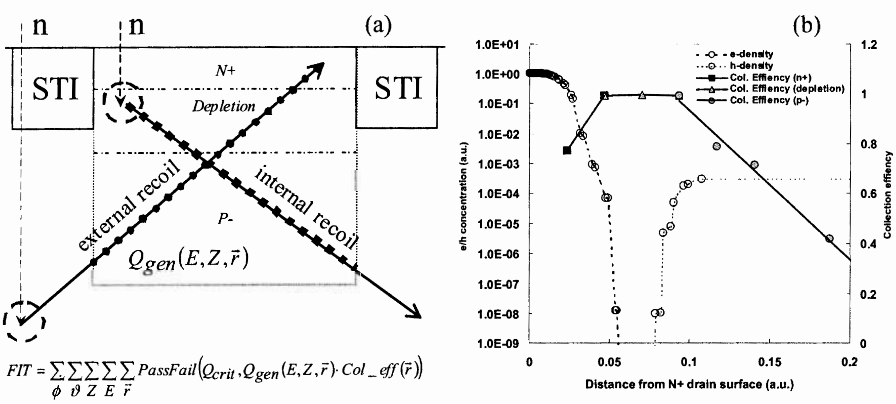
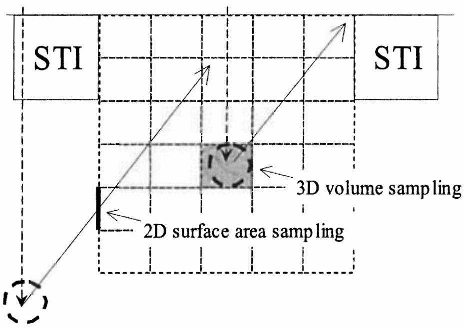



**Fig. 4** (a) Charge generation model and the general equation for charge collection and FIT calculation; (b) Charge collection efficiency derived from 3D device simulations and its correspondence to the S/D-to-well junction doping profile

## 4 Statistical Algorithms for FIT Simulation

A random recoil ion event consists of seven variables: recoil angles (ϕ, θ), ion nuclear number Z, ion kinetic energy E, and recoil starting location (x, y, z). The distribution associated with ϕ and θ is typically assumed to be uniform for the non-elastic scattering events and is sampled linearly. The distribution associated with Z and E can be obtained from Fig. 2a and is sampled with a prioritized order. The distribution associated with the recoil starting location is uniform but not limited to the charge collection box underneath the S/D area, thus making it difficult to capture the contribution of "external" recoil ions. As shown by Fig. 5, a novel technique was developed to use segmented surface areas to count the cumulative probability of external recoil ions entering the charge collection box and the internal cubes to count the probability of "internal" recoil ions.




Total Ion Probability = $TP(E_I, Z)$

For 3D volume sampling of internal recoils

$$TP(E_I, Z) = V_{sampling} \cdot WP(E_I, Z)$$

For 2D surface sampling of external recoils

$$TP(E_I, Z) = S_{sampling} \cdot \int_{E_I}^{E_{max}} \frac{WP(E, Z) \cdot (\hat{n} \cdot \hat{r})}{(dE/dR)} \cdot dE$$

$\hat{n}$ and $\hat{r}$ are the unit vectors of sampling surface and ion path

**Fig. 5.** The novel technique for effective sampling of recoil ions initiated inside and outside the charge collection box underneath S/D area. The surface area sampling comprehends all recoil ions initiated outside but eventually entering the box.

## 5 Results and Discussion

Fig. 6a shows the simulated and experimentally measured neutron-SER FIT rates of SRAMs fabricated using 0.18μm technology. While the models and simulation algorithms are developed for logic products, SRAMs are usually the most convenient vehicle for verification and calibration. The physical-model-based statistical simulation of neutron SER agrees with the experimental data very well without using any fitting parameters. Both simulated and measured results show a power-law dependence between the FIT rate and $Q_{CRIT}$, which is different from the exponential relationship observed from alpha SER. [3] By examining the SER contribution of each type of recoil ion, as shown in Fig. 6b, we find that each ion type does obey the exponential dependence on $Q_{CRIT}$, just as alpha particles do, revealing the same fundamental SER physics masked by the collective behavior of recoil ions. The simulated results also show a saturation trend at very low $Q_{CRIT}$, similar to what has been reported before for alpha-SER because of the dominant contribution from secondary alpha particles. [3] At very high $Q_{CRIT}$, the simulation results show a fast roll-off behavior, which can be physically explained by the exclusive contribution from heavy recoil ions that bear the exponential dependence to make neutron-SER roll off faster than what a power-law predicts. Both trends are extremely critical for accurate SER modeling as well as technology and design planning.

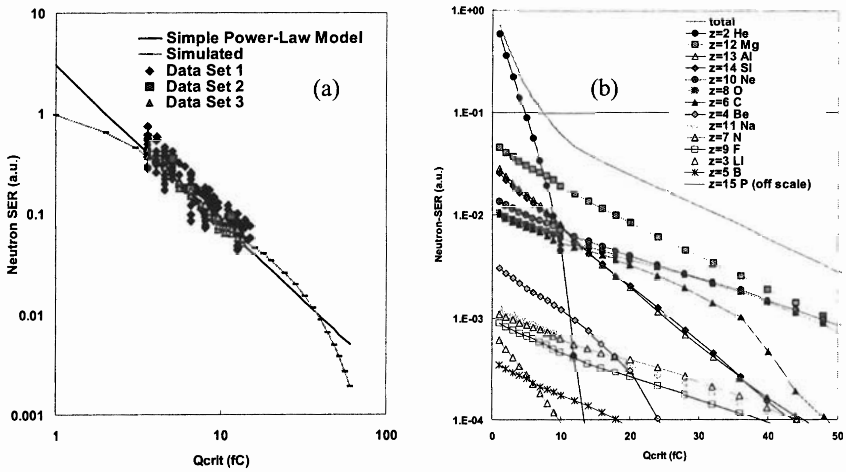



**Fig. 6.** (a) The simulated and experimentally measured neutron-SER FIT rates of the SRAMs fabricated using 0.18mm logic technology. As a collective behavior of neutron-SER, a power-law dependence on $Q_{CRIT}$ is observed; (b) SER contribution of each type of recoil ion that obeys an exponential dependence on $Q_{CRIT}$. The total neutron-SER is dominated by secondary alpha particles at low $Q_{CRIT}$ region and heavy ions at high $Q_{CRIT}$ region.

## 6 Conclusions

A new and physical neutron-SER modeling and simulation approach has been developed with excellent accuracy demonstrated on SRAMs fabricated using 0.18μm CMOS technology. The SER contribution of each type of recoil ion and a fast roll-off behavior at high $Q_{CRIT}$ are reported for the first time.

## Acknowledgements

The authors would like to thank H.H.K. Tang of IBM, S. Maston, J. Bordelon and N. Mielke for their critical contribution to this work.

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