Critical Charge Characterization for Soft Error Rate Modeling in 90nm SRAM

Riaz Naseer, Younes Boulghassoul, Jeff Draper
Information Sciences Institute
University of Southern California
Marina Del Rey, CA 90292 USA
{naseer, yboulgh, draper}@isi.edu

Sandeepan DasGupta, Art Witulski
Institute for Space and Defense Electronics
Vanderbilt University
Nashville, TN 37235-1553 USA
{sandeepan.dasgupta, art.witulski}@vanderbilt.edu

***Abstract*— Due to continuous technology scaling, the reduction of nodal capacitances and the lowering of power supply voltages result in an ever decreasing minimal charge capable of upsetting the logic state of memory circuits. In this paper we investigate the critical charge (Q_{crit}) required to upset a 6T SRAM cell designed in a commercial 90nm process. We characterize Q_{crit} using different current models and show that there are significant differences in Q_{crit} values depending on which models are used. Discrepancies in critical charge characterization are shown to result in under-predictions of the SRAM's associated soft error rate as large as two orders of magnitude. For accurate Q_{crit} calculation, it is critical that 3D device simulation is used to calibrate the current pulse modeling heavy ion strikes on the circuit, since the stimuli characteristics are technology feature size dependant. Current models with very fast characteristic timing parameters are shown to result in conservative soft error rate predictions; and can assertively be used to model ion strikes when 3D simulation data is not available.**

I. INTRODUCTION

Soft errors pose a major threat to system reliability in today's deep sub-micron technologies. Technology scaling relies on reduced nodal capacitances and lower voltages, to improve performance and power dissipation, as well as shrinking dimensions to increase layout density. This in turn also reduces the critical charge (Q_{crit}) required to upset a circuit node, making these sub-micron technologies more susceptible to soft errors. The increased density of modern chips raises the likelihood of having a large number of soft errors per chip. For ground-level applications, e.g., high-end servers, networking switches and database applications, the reliability of the computing machine is as important as its performance. The problem becomes even more acute for aircraft and space electronics where high-energy neutrons (at high altitudes), as well as protons and heavy ions (in space) are more abundant. Due to the increasing severity of the soft error problem, there is a growing trend in the community to adopt soft error rate as a design parameter along with the more common power, area and speed trade-offs [1].

Critical charge (Q_{crit}) is generally defined as the minimum amount of charge that must be collected by a circuit, following the strike of an ionizing particle at a sensitive node, in order to change the state of the circuit [2]. Technology Computer Aided Design (TCAD) tools provide a great help in modeling the effects of radiation on circuits at various technology nodes. Device level 3D simulations, in particular, are very helpful for accurately predicting the behavior of those devices since they have the clear advantage of modeling the actual geometry of the target device, as well as incorporating underlying physical mechanisms (e.g. charge deposition, charge collection efficiency) when generating each current pulse stimulus.

The space electronics community generally uses TCAD tools for Q_{crit} characterization and soft error rate estimation, when no test data are available, but the circuit community usually relies on various SPICE-level current models [2]-[1] to compute the critical charge metric [5]-[8]. The shape and amplitude of the current model have a strong effect on the computation of Q_{crit}. Therefore, it is important to calibrate these current models to 3D device simulations for every technology generation. In this paper, we use 3D device simulations to characterize the Q_{crit} of a 6T SRAM cell designed for the 90nm technology, and determine the double-exponential current model that best fits the stimulus from 3D simulation. This calibrated model and other models available in literature are then used to characterize Q_{crit} for the same SRAM cell.

Simulation results reveal that Q_{crit} values computed from 3D device simulation currents are 3 times smaller than those found using current models from the literature. Since Q_{crit} is the primary input to various error prediction models, the accuracy in its determination is fundamental for reliable soft error rate predictions. This implies that SER calculations based on the higher spectrum of Q_{crit} values may be dangerously under-estimating the real SER risk. Using the Q_{crit} values obtained with the various presented models, the SER of the unhardened SRAM implemented in this work is shown to vary by up to two orders of magnitude for the Van-Allen proton belt radiation environment case. Such a discrepancy has long-reaching implications on the applicability of mitigation techniques targeted to specific radiation environments.

The rest of the paper is organized as follows. Section 2 describes multiple models used in literature to characterize Q_{crit} for SRAM cells. Section 3 discusses the current profile obtained using 3D device simulations and a best fit model to this current. In section 4, we compare simulated Q_{crit} values from the generic models versus our 3D model, present bit error rates based on these Q_{crit} values, and then discuss the discrepancies observed in the results. Section 5 concludes the paper.

II. Ion Current Models for Q_{crit} Characterization

Q_{crit} for SRAM cells is generally defined as the minimum amount of charge that needs to be deposited by an incident ion (or collected by the struck node) in order to upset the logic state of a memory cell. The radiation-induced photocurrent resulting from an ion strike is characterized by two collection phases: a first phase of E-field accelerated free carrier motion (fast drift current), followed by a second phase of charge collection due to free carrier density gradients (slow diffusion current). The regions most sensitive to ion strikes are reverse-biased junctions, because of the E-field present across their large space charge region, hence efficiently collecting any charge generated in their vicinity. In modern 6T SRAM designs, the off-NMOS drain is the most sensitive region of the cell (in addition to the off-PMOS and high-Z NMOS drain regions) due to the combined effects of increased electron mobility and design practices favoring the speed at which a cell can flip states.

3D TCAD tools can achieve a great level of accuracy, but consequently, also suffer from large computation times as well as limited capabilities to simulate circuits exceeding relatively small sizes. Therefore, it is desirable to model radiation strikes as current sources that can be easily injected in the target circuit for fast SPICE simulations. Figure 1 shows an SRAM cell and its corresponding current source, modeling a heavy-ion strike on the off-NMOS drain, applied across the drain and grounded source terminals.

A number of current models have been proposed in the literature over the years and they are used by the circuit community to characterize Q_{crit} by performing SPICE simulations. A simplified model was proposed by Roche et al in [4], using 3D device simulations in 0.35μm technology. According to their definition, Q_{crit} can be found using:

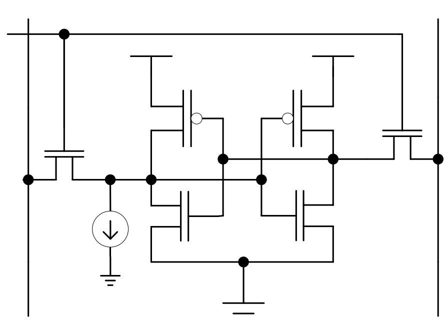

Figure 1. SRAM cell with off-nmos strike model

$$Q_{crit} = C_N \cdot VDD + I_{DP} \cdot T_F \qquad (1)$$

where C_N is the node capacitance, VDD is the supply voltage, I_{DP} is the maximum drain conduction current of the PMOS (provided the strike is made at the OFF NMOS drain) and T_F is the flipping time of the cell. The computation of T_F involves 3D device simulation where the transient voltage of the opposite node (not struck by the incident ion) in the SRAM cell is observed during the flipping of the cell. In order to characterize Q_{crit} by SPICE simulations only, it was proposed that the $I_{DP}.T_F$ term can be ignored from equation (1) and Q_{crit} can be found by integrating an exponentially decaying current ($I_0.\exp(-\tau)$) with small time constants which are less than 20ps. The target value of the magnitude of the current (I_0) and the time constant of the exponential (τ) are achieved when the product $I_0.\tau$ is minimized. The resulting Q_{crit} by this method will be slightly under-estimated because of neglecting the additive term.

Another current model proposed by Freeman [3], to compute Q_{crit} for bipolar memories, has also been used for finding Q_{crit} for a CMOS SRAM cell as in [6],[8]. Freeman's model is described by equation (2) and defines current in terms of total charge deposited (Q) by the ion and a single timing parameter τ.

$$I(t) = (2/\sqrt{\pi}).(Q/\tau).(\sqrt{(t/\tau)}).\exp(-t/\tau) \qquad (2)$$

A diffusion collection model given by equation (3) has been used in [5],[6] and is considered more suitable for modeling neutron strikes. The time t_{max} represents the instant when the maximum value of the current I_{max} is reached.

$$I(t) = I_{max}\,[e.(t_{max}/t)]^{3/2}\,[\exp(-3t_{max}/2t)] \qquad (3)$$

Finally there is the most commonly used model by the circuit community (given by equation 4) which is a double exponential pulse with two timing parameters τ_r and τ_f, representing the rising and falling time constants of the exponentials. This model has been widely used in the literature to find not only the Q_{crit} but the single event transients (SET) introduced by ion strikes in combinational logic [7].

$$I(t) = (Q/(\tau_f - \tau_r)\,[\exp(-t/\tau_f) - \exp(-t/\tau_r)] \qquad (4)$$

The current pulse rise and fall times, and their full-width at half-maximum (FWHM) strongly affect the

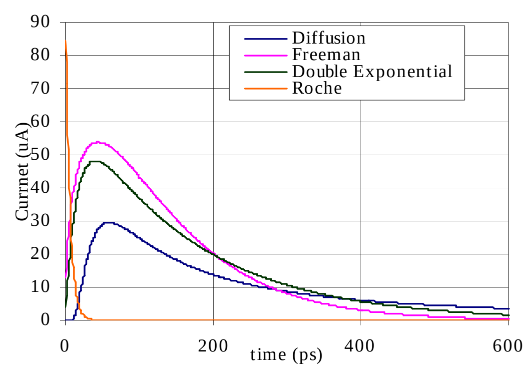

Figure 2. Ion current pulse profiles

characterization of Q_{crit}, to the point where each pulse model results in its own Q_{crit} value. Hence the characteristic timing parameters of the above models for one technology node cannot be extrapolated directly to the next technology node. Some empirical approximations have been used in the literature to select values for these parameters. Figure 2 shows the current pulses derived using such empirical approximations, where the FWHM is 161ps for a total charge of 10fC as considered in [6]. On the other hand, the Roche model does not have the requirement of specific FWHM and we see in Figure 2 that it has a very fast fall time with relatively large peak amplitude as compared to other models.

III. CURRENT PROFILES FROM 3D DEVICE SIMULATIONS

3D device and mixed-mode simulations are computation intensive and require a fairly long development and calibration phase in comparison to SPICE-type circuit simulations. However, they are also able to model complex physical mechanisms and geometry-related phenomena that cannot be captured by circuit simulations, and that can potentially affect parameters relevant to the calculation of Q_{crit} (e.g. charge collection depth, charge collection area and charge collection efficiency).

The 3D simulations were performed using ISE-TCAD 10.0 Dessis. The transistors' 3D models were calibrated for both high and low V_{DS} over a range of 0 to 1.2 V to reproduce the DC transistor characteristics as defined in the manufacturer's process design kit (PDK) within a 5% error margin. In the initial set of simulations, the modeled 90nm SRAM cell was subjected to ion strikes with LETs (linear energy transfer) ranging from 1 to 20 MeV-cm^2/mg. The SRAM cell exhibited a very high sensitivity to radiation, as it got upset for an LET of 1 MeV-cm^2/mg. A second set of simulations with LETs ranging from 1 to 0.1 MeV-cm^2/mg fine-tuned the investigation of the LET threshold and determined it to be very close to 0.25 MeV-cm^2/mg. Figure 3 shows current profiles resulting from the simulation of ion strikes on the off NMOS drain, over LETs ranging from 0.1 to 1 MeV-cm^2/mg.

It is interesting to note that photocurrent pulses from low LET heavy ions (~1 MeV-cm^2/mg or less) have profiles that can be quite closely described by a double exponential pulse. It should also be mentioned here that such property is no longer valid for pulses from higher LET ion, such as 10 and 20 MeV-cm^2/mg, where the tail portion on the radiation-induced photocurrent shows distortions from extended charge collection (deep carrier diffusion), hence cannot be described by a simple decaying exponential function. Therefore, a double exponential pulse cannot model correctly all instances of heavy ion strikes, and should be used with caution.

In this work, for LET values below 1 MeV-cm^2/mg, the characteristic parameters of TCAD photocurrents (rise time, fall time, peak amplitude) were used to define double exponential current pulses for ion strike simulations. The amplitude of the fitted double-exponential pulse was modulated to find the upset/no-upset boundary for the SRAM cell. Figure 3 shows a double-exponential pulse with time characteristic parameters matched to 3D simulation results, and with amplitude modulated to find the smallest pulse capable of inducing cell upset.

IV. SIMULATION RESULTS AND DISCUSSION

The simulated SRAM cell was designed using foundry-provided high-density layout rules from a commercial 90nm process. To simulate the SRAM cell, a netlist was first extracted using the Virtuoso Layout editor and converted to equivalent subcircuit calls in order to use the appropriate transistor models provided in the manufacturer's PDK. Charge collection from ion strikes was modeled by applying respective current sources across the terminals of the "hit" transistor in the memory cell (Fig. 1). HSPICE was used for circuit simulation of the SRAM's radiation response, with a 1V power supply bias and under standard room temperature conditions (25°C). Table I presents the simulated Q_{crit} values for all the models investigated in this study.

The results in Table I reveal that the Q_{crit} values computed from the Roche et al and the best fit double exponential models are closer to the Q_{crit} value derived from 3D simulations. All other models are over-estimating the Q_{crit} by almost a factor of three. The reason for the best-fit double-exponential model resulting in a slightly lower Q_{crit} is the timing characteristics of the current, emphasizing that even small variations in current profiles may result in Q_{crit} inaccuracies. As for the Roche model, the under-estimation of Q_{crit} can be partially attributed to the ignored factor $I_{DP}.T_F$ in expression (1) which, if properly accounted for, will slightly increase Q_{crit}. In general, the double exponential model best-fitted to the 3D pulse and the Roche model will result in Q_{crit} under-estimations with reasonable error margins. All other models will result in large Q_{crit} over-estimations, unless calibrated with the 3D simulation on the technology node of interest.

Based on the Q_{crit} values presented in Table I and the sensitive area cross-section extracted from cell layout, we estimated the bit error rate (BER) of the SRAM under consideration, using the CREME96 radiation environment

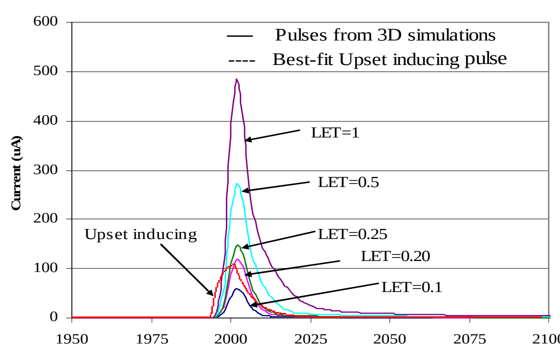

Figure 3. 3D simulation current pulses for LET < 1MeV-cm^2/mg

TABLE I. Q_{CRIT} VALUES USING DIFFERENT MODELS

Model	Timing Parameters (ps)	Q_{crit} (fC)
3D TCAD Simulation	(LET=0.25MeV-cm^2/mg)	1.40
Double exp fit to 3D	τ_r = 2.5, τ_f = 5.5	1.15
Double Exponential	τ_r = 33, τ_f = 161	4.07
Double Exponential	τ_r = 16, τ_f = 161	4.09
Roche et al	τ = 2	0.95
Freeman	τ = 90	3.90
Diffusion	t_{max} = 60	3.58

TABLE II. BIT ERROR RATES (IN ERRORS/BIT-DAY) USING Q_{CRIT}

Model	GEO Orbit (Max GCR)	Solar Flare (worst week)	Proton Belt
3D TCAD Simulation	1.31e-6	2.23e-3	4.87e-3
Double exp fit to 3D	1.66e-6	3.944e-3	9.1e-3
Double Exponential	3.61e-7	7.66e-5	3.7e-5
Double Exponential	3.59e-7	7.54e-5	3.49e-5
Roche et al	2.08e-6	6.64e-3	1.58e-2
Freeman	3.93e-7	8.66e-5	4.72e-5
Diffusion	4.43e-7	1.1e-4	7.6e-5

modeling tool [9]. Table II shows the BER in errors/bit-day for three environments; (1) geosynchronous orbit at solar minimum/maximum galactic cosmic ray condition (GEO Orbit – MAX GCR), (2) Solar flare condition averaged for the worst week or 99% worst case model, and (3) 3000km equatorial orbit for Van Allen Belts at near-peak trapped proton flux.

For the GEO orbit scenario, the spread in BER for various models is within an order of magnitude difference. For the proton belt and solar flare environments, the spread in BER between the models is quite large. It can be observed from Table II that the double-exponential models with empirical parameters, the Freeman model, and the Diffusion model are all under-estimating the BER by two orders of magnitude, compared to the BER calculated from TCAD simulations.

When compared to 3D TCAD simulation, the Roche model results in an over-estimation of BER by an order of magnitude for the trapped protons scenario while differences for the other two environments vary between two to three times. The best-fit double exponential current results in comparable BERs for the GEO orbit case; while the BER for the other two radiation environments is almost the double of what is predicted from TCAD's Q_{crit}. The best-fit double-exponential and Roche models result in conservative over estimation of the BER without compromising reliability.

V. CONCLUSION:

We have investigated the critical charge required to upset high-density SRAM memory cells designed in a commercial 90nm technology. The resulting current pulses from 3D simulations are process and LET specific. The current profiles for LETs less than 1 MeV-cm^2/mg can be modeled with double exponential pulses with appropriate characteristic parameters and result in conservative BER predictions. Generalized models from simulations on earlier technology nodes may result in large over-estimation of Q_{crit} (almost 3 times for a 90nm process) and hence a wide under-estimation of soft error rates (such as two orders of magnitude difference for the trapped radiation belts).

The use of generic current models to compute Q_{crit} and hence the BER of a system may potentially result in compromising over-all system's reliability. The Q_{crit} of 1.4fC, for commercial high-density 90nm SRAM cell, found using 3D simulations corresponding to an LET of 0.25MeV-cm^2/mg, implies that sub-100nm technology ICs will get upset from ions (such as trapped protons in radiation belts) which have much larger flux than heavy ions. Due to this sensitivity of nano-meter technologies to protons, a 3x difference in Q_{crit} modeling error may result in a two order-of-magnitude difference in effective bit error rate. This has strong and far-reaching implications for the micro-electronics used in communication satellites which operate in the trapped radiation belts zone. Current models with very fast characteristic timing parameters (less than 20ps), such as Roche model and double-exponential model, result in conservative bit error rate predictions. Therefore, these models can assertively be used for circuit's radiation response simulation when TCAD 3D simulation data is not readily available.

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