# Microdose analysis of ion strikes on SRAM cells

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***ABSTRACT***

The effect of ion radiation on SRAM microstructures is analyzed. The voltage at which a cell cannot hold a programmed state changes with microdose. SPICE simulations and physical analyses support experimental data.

A method of measuring the effect on microstructures from exposure to highly localized ionizing radiation is described. The voltage at which a commercial SRAM cell cannot hold a programmed state changes with microdose. This technique facilitates analysis of the microdose distribution across the array, in addition to the analysis of the occurrence of anomalous shifts in operating bias due to rare, large energy-deposition events. SPICE codes are used to analyze the damage to individual cells and the response of an SRAM cell, as well as analysis of basic device physics.

**Introduction**

With space missions employing large amounts of high-density memory, the effect of damaged bits on a memory bank may exceed any EDAC built into the system. This result may have dire consequences for long-term space missions. Bits damaged by radiation is a total dose effect on a very small scale. Heavy ions or even protons damage the microscopic structures of modern ICs. Microdosimetry is the study of dose deposition on the microscopic scale.

Heavy ion radiation deposits dose in electronic devices in highly localized tracks [1]. The local area of the strike receives a large dose while the areas juxtaposed to but outside the strike will be unaffected. The device struck by radiation will exhibit an effect due to the damage from the dose. Many technologies experience this type of damage to a single microstructure. SRAMs, DRAMs, and some nonvolatile technologies exhibit damage to memory cells and some of the peripheral circuitry [2,3]. This damage results in Single Hard Errors (SHE), catastrophic Single Event Functional Interrupt (SEFI), and decreased performance. Studies concerning the effects of dose from a single ion on the parameters of a memory cell have been conducted [4,5]. This study investigates the microdosimetric response of SRAM cells like the one similar to that shown in Figure 1.

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**Theory and Setup**

Figure 2 shows data typical of an SRAM irradiation by heavy ions and read out at various voltages [2]. The number and magnitude of the radiation-induced outliers were observed to depend predictably on fluence. These data do not address some key phenomena of SHE. The foremost of these effects is the effect of multiple ion hits on an SRAM and the recovery effect seen in some bits.

A single hit of a heavy ion is expected to deposit a large dose in the local area of the strike. Since the definition of dose is based on a macroscopic model, the dose that a single ion deposits must be treated carefully. Accurate estimations can be made, however. Starting with the definition of dose:

$$D[rad] = 1.6x10^{-5}\Phi L \qquad (1)$$

where $\Phi$ is the fluence of the radiation (in $cm^{-2}$) and L is the LET (in $MeV/mg/cm^2$). The track of a single ion produces a column of charge with an exponentially decreasing charge density outward from the ion track. The fluence of a single ion hit over the area of the ion track is approximately equivalent to the fluence of uniform irradiation, i.e., ion hits spaced one radius apart. This is equivalent to

$$\Phi = \frac{1}{A_{OneTrack}} \qquad (2)$$

where A is the area of the ion track. The radius of an ion track ranges from 0.1um to 1um [1]. This means that the effective fluence of a 1um ion track is $10^8$ $cm^{-2}$ and the dose to the area at the ion strike is 1.6 krad per LET. A 0.1um ion track, therefore, results in a microdose of 0.16 Mrad per LET.

The analytical value of the flip voltage that an SRAM exhibits can be derived from first principles. The SRAM cell fails when both transistors of an inverter can no longer remain on. This condition means current in both transistors in the inverter is flowing. With no loss of generality, this condition is

$$R_{PMOS} = R_{NMOS} \qquad (3)$$

where R is the resistances of the transistors. It follows that

$$\frac{V_{DS}^n}{I_{DS}^n} = \frac{V_{DS}^p}{I_{DS}^p} \quad (4)$$

where $V_{DS}$ is the voltage across the source and drain of a transistor and $I_{DS}$ is current through a transistor channel. It has been observed that the flip voltage occurs in the saturation region and the subthreshold region of transistor action. The saturation current in a MOS transistor is given by

$$I_{DS} = K\left(\left(V_g - V_t\right)V_{DS} - \frac{m}{2}V_{DS}^2\right) \quad (5)$$

where K and m are constants. $V_g$, $V_t$, and $V_{DS}$ are the gate, threshold, and drain source voltages, respectively. After inserting Eq. 5 into Eq. 4 for both the PMOS and NMOS case, algebraic manipulations result in the flip voltage condition

$$K_{n0}V_g^n + K_{P0}V_g^p = \left|K_{n0}V_t^n\right| + \left|K_{P0}V_t^p\right| \quad (6)$$

where $V_g^n$ is the gate to source voltage on the NMOS transistor and $V_g^p$ is the gate to source voltage on the NMOS transistor. $V_t^n$ is the threshold voltage of the NMOS transistor and $V_t^p$ is the threshold voltage of the PMOS transistor. The absolute value bars are inserted for ease of application. Also with no loss generality, ICs can be designed such that $K_{n0} = K_{p0}$. Therefore,

$$V_g^n + V_g^p = \left|V_t^n\right| + \left|V_t^p\right|. \quad (7)$$

Now considering the node that causes the error is the one held high at the gates, $V_g^n = 0$ and $V_g^p = Vcc$, where Vcc is the supply voltage of the SRAM. Therefore, the condition of a voltage at which an SRAM cell can no longer hold its programmed state is

$$Vcc = \left|V_t^n\right| + \left|V_t^p\right|. \quad (8)$$

Identical treatment of the sub-threshold current expression for the configuration yields the same result. One important note is that Eq. 8 was derived by assuming K and m are not affected by an ion strike. K and m contain a $C_{ox}$ term and therefore the result of Eq. 8 may be much more complex. The full paper will fully derive the sub-threshold case as well as a completely general derivation.

The effect of an ion hit on the threshold voltage depends on the thickness of the gate oxide. Explicitly,

$$\Delta V_t = \frac{qN}{C_{ox}} \quad (9)$$

where q is the fundamental charge, N is the amount of trapped charge, and $C_{ox}$ is the capacitance of the oxide. The amount of charge deposited by an ion is

$$N = \frac{Lt_{ox}\rho}{W} \quad (10)$$

where $t_{ox}$ is the oxide thickness, ρ is the density, and W is the pair creation energy. Now Eq. (10) should not be inserted generally into (9) since the amount of trapped charge will be field dependent, and the amount of recombination in oxide will be dependent on charge density [1]. The general relation between applied field and trapped charge is given by Jaffe [1]. This results in

$$\Delta V_t = \frac{qt_{ox}\rho Y(E)Z(L)}{WC_{ox}} \quad (11)$$

where Y is the charge yield function as a function of applied field, E, and Z is the charge yield function as a function of LET, which is presently unknown. Eq. 11 predicts two important effects; the shift in threshold voltage is strongly dependent on applied field and on LET similar to other SEE phenomenon. Previous studies show that for LET values greater than 30 Mev/mg/cm$^2$ the dependence of shifts in SRAM cell is not large [2]. One would expect that the behavior of these shifts at lower voltage correlates to SEU behavior. This model neglects charge injection from the substrate, thin oxide effects, and interface effects. The field oxide and the bird's beak structure are also expected to affect response [1]. These effects will be included in the full paper.

The setup of the experiments in the research are outlined elsewhere and will only be summarized here [2]. The SRAMs that are tested here are operated at lowered voltages using a voltage level shift board. The SPICE simulations use standard codes and models. Macroscopic SRAMs cells were also constructed explicitly to test the results of radiation on specific transistors. These test SRAM cells were created out of discrete MOSFETs, and programmed and read manually.

**Results**

SPICE Code Simulation

SPICE code simulations of an SRAM cell were done for comparison with the experiments. The threshold is set with the Vto option. This is the simplest method used to change the threshold of a transistor using SPICE code and has been shown to accurately describe basic circuit response for using SPICE to analyze radiation effects [6]. Figure 3a shows the response of the output of an SRAM cell as the Vcc voltage is ramped down. At a sufficiently low voltage, the node that is set low (the O symbol) rises abruptly and will then register an error. Figures 3b, 3c, and 3d show a similar simulation when the Vto of a PMOS transistor is set to 1.7, 2.7, and 3.7 volts, respectively. For the threshold of 3.7 volts shown in Figure 3d, one can see that the SRAM cell cannot hold the state set by the netlist and immediately records an error. This effect correlates to a SHE in an SRAM.

Another important observation is that the change in the voltage at which an error occurs is linear with the change in the threshold voltage of a transistor. The corollary of this effect is that the sensitivity of the SRAM based micro-dosimeter is not affect by the SRAM circuit, but only the sensitivity of the affected transistor to dose. Finally, the results of Figure 3 agree very well with the prediction of Eq. 8. Figure 3b also shows that regardless of the threshold values of the transistors, there is a voltage at which no data can be stored in an SRAM. The voltage at which this limit occurs is the flip voltage of the undamaged inverter.

The full paper will develop these results. Foremost the question of the result of ion strikes on different transistor gates and multiply struck will be resolved. Previous data show that under higher fluences, some SRAM cells showed lower flip voltages than previous fluence levels. This would indicate that a multiply hit cell might be less susceptible to

SHE due to more than one MOSFET threshold voltage changing.

Macroscopic test cell

An SRAM cell was constructed out of discrete transistors to test the effect of radiation damage on one or two of the transistors in an SRAM cell. This technique specifically damages any combination of the four FETs. Figure 4 shows the shift in threshold voltage of a NDS9958 PMOS transistor exposed to Cobalt-60 gamma rays. The shift is negative and linear, which is typical of the response of this device. Figure 5 depicts the voltage at which an SRAM can longer hold its programmed state. The response in Figure 4 strongly correlates with that of Figure 5. This result agrees with SPICE predictions that threshold shift and error voltage are linear in their relationship. The flip voltage with no irradiation agrees with Eq. 8. The measure threshold of the two transistors $V_t^p$=-1.6V and $V_t^n$=1.4V. $I_0$ is the same for both transistors. For experimental purposes, the flip voltage condition was $R_{PMOS}=4*R_{NMOS}$. The resulting flip voltage is calculated to be 1.95V. This result differs by only 2.5% from the measured value at pre-irradiation.

The macroscopic SRAM cell differs from the SRAM under test in several ways. Foremost, the discrete transistors used in the cell were irradiated with gamma radiation that will damage the oxide differently from a heavy ion striking a MOSFET in an IC. Rosenfeld et al. showed, however, that discrete MOFETs could still be used in microdosimetry methods [7]. Irradiations of the discrete SRAM circuits with heavy ions will be done to clarify this point. Also, the discrete SRAM cells are not monolithic and, therefore, the substrates are not common to one another. This may change the biasing conditions of the devices. Also, the exact circuit of the IC SRAM is not known due to manufacturer silence. Parasitic capacitances, incidental and deliberate rectifying junctions, and device behaviors, like characteristic I-V curves are unknown and can only be estimated. DPA has been done on both the IC and discrete DUTs to determine some of this information and the results will be included in the full paper.

Applied field dependence

Figure 6 presents the results of Toshiba SRAM irradiated to 2e7 $cm^2$ with ions of LET=30 MeV/mg/$cm^2$. When an SRAM is powered, each of the gates of the transistors is under bias. The voltage across the source and drain of two of the FETs, a PMOS and NMOS, is zero so the field is uniform across these gates. The other two FETs have differing biases on the source and drain so that field is present on only the drain side of these two transistors. Therefore, lowering the bias of these irradiations should change the flip voltage. The data in figure 6 agrees with Jaffe's model of charge yield from heavy ion tracks in oxides. Poisson uncertainty determines the error bars. The full paper will study bias dependence in depth in depth.

**Discussion**

This paper will study the effects of heavy ion hits on the microstructures of COTS SRAMs. Several issues remain from previous studies on small volume effects. These are

1. The exact sensitive volume of SHE in SRAMs.
2. The effect of the Si-SiO2 interface on microdose response.
3. The vacillating bit values as SRAM bias is decreased.
4. The effect of multiple hits on an SRAM cell.

These issues will be addressed in the full paper as well as the ones raised in this summary. All four approaches presented here will be used to resolve these issues.

**Conclusion**

Ionizing radiation changes the lowest operating bias at which an SRAM can be read out for heavy ions. Reading the data does not destroy or alter the data, nor does it prevent continued measurement with the same device.

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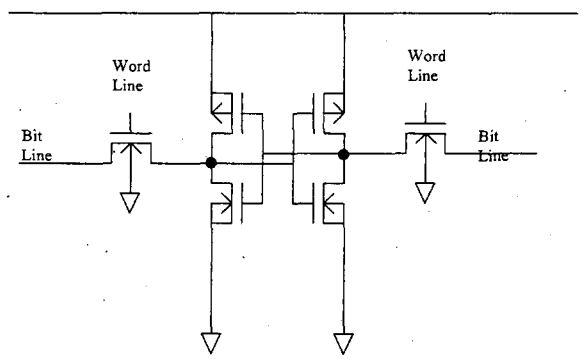


Figure 1. A typical 6T CMOS SRAM.

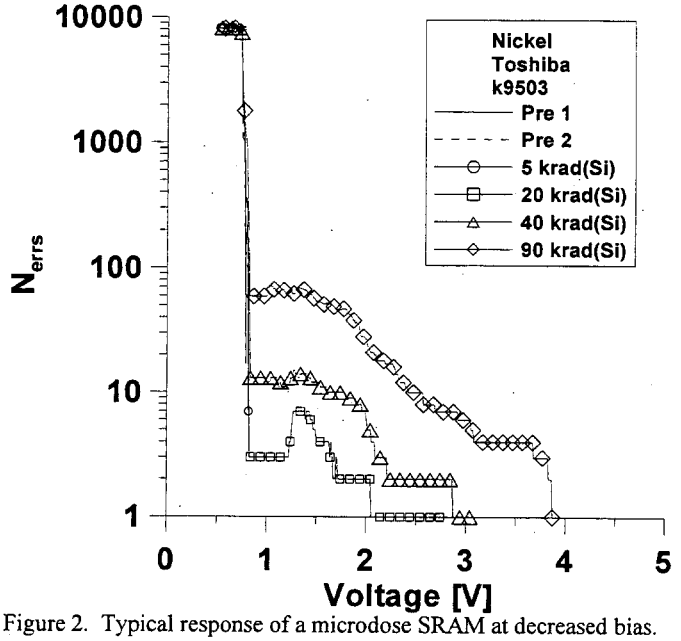


Figure 2. Typical response of a microdose SRAM at decreased bias.

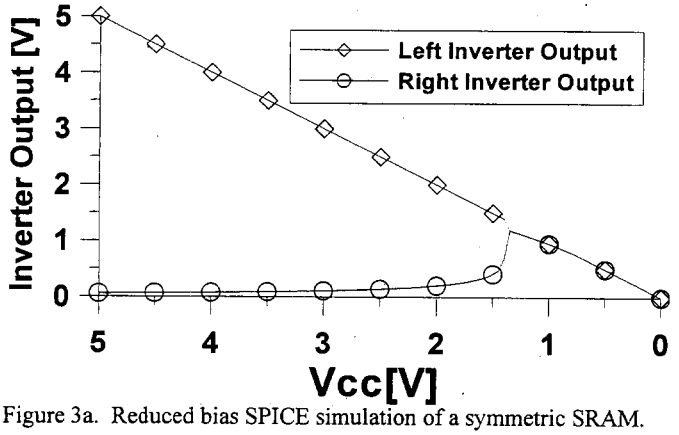


Figure 3a. Reduced bias SPICE simulation of a symmetric SRAM.

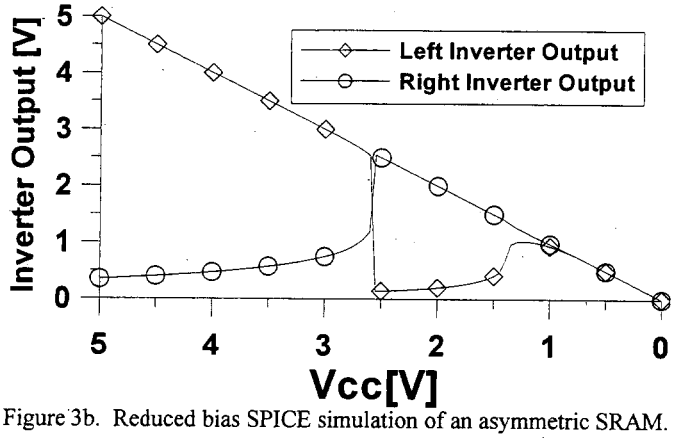


Figure 3b. Reduced bias SPICE simulation of an asymmetric SRAM.

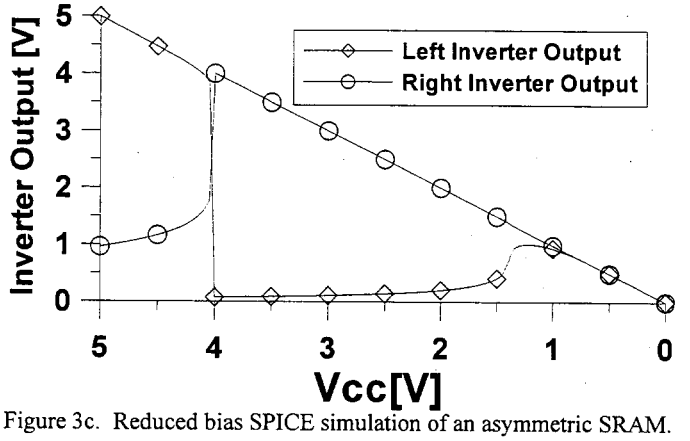


Figure 3c. Reduced bias SPICE simulation of an asymmetric SRAM.

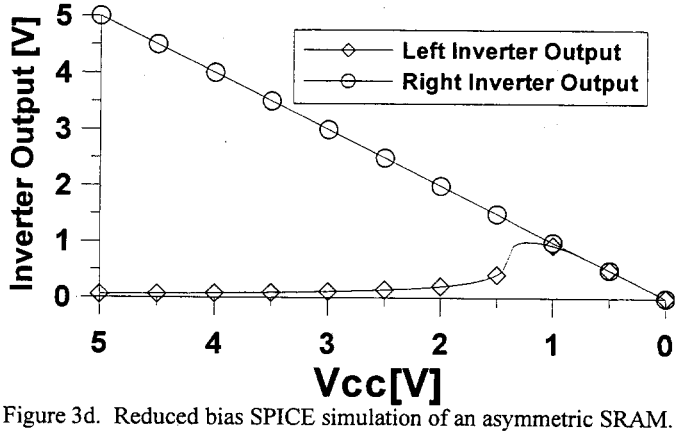


Figure 3d. Reduced bias SPICE simulation of an asymmetric SRAM.

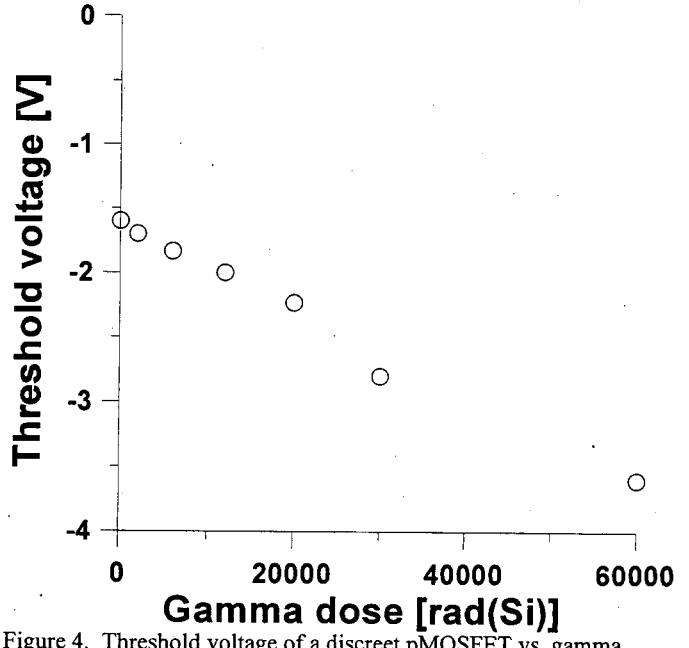


Figure 4. Threshold voltage of a discreet pMOSFET vs. gamma dose.

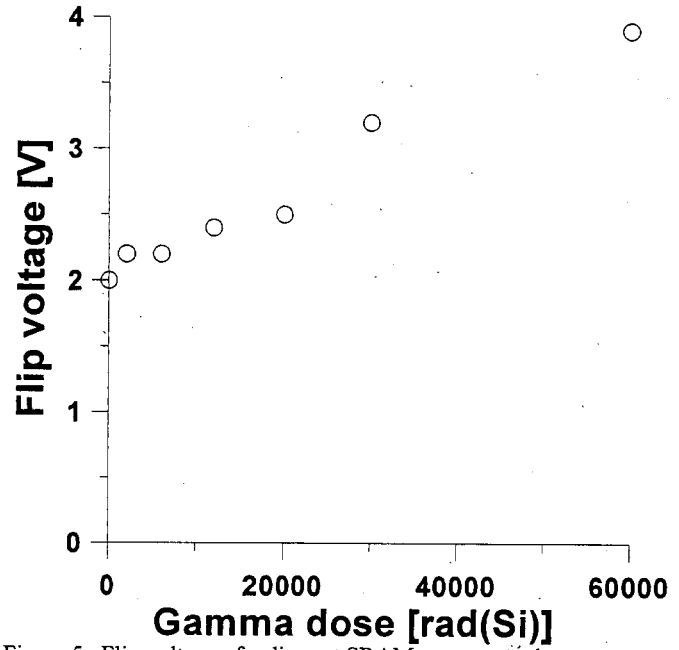

Figure 5. Flip voltage of a discreet SRAM vs. gamma dose.

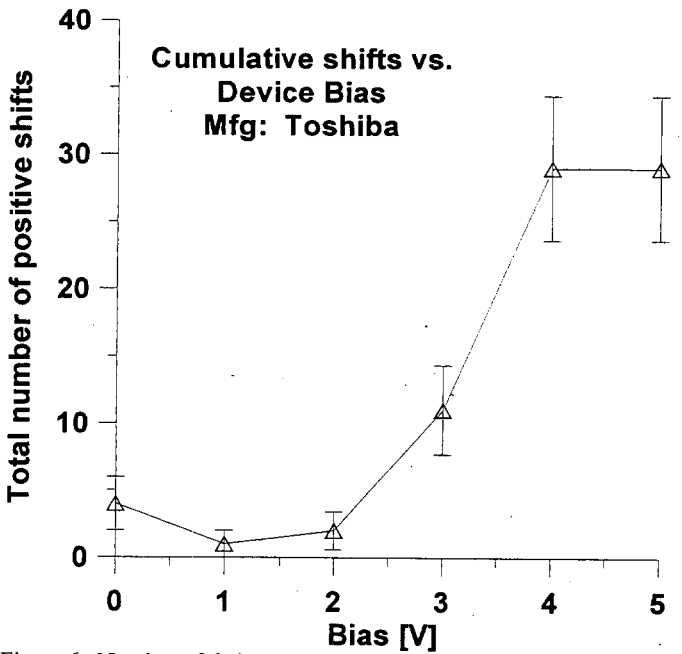

Figure 6. Number of 6 sigma event as function of irradiation bias.