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Analysis of Radiation Effects on Individual DRAM Cells

Leif Z. Scheick, Steven M. Guertin, and Gary M. Swift

***Abstract*--A novel way to measure the radiation characteristics of DRAM memory cells is presented. Radiation exposure tends to drive retention times lower for cells. The change in retention time (the time period required for a cell to upset without refreshing) is used to measure the effect of irradiation on the DRAM cells. Both the radiation response of a single DRAM cell and the response of all cells as a statistical whole are analyzed.**

I. INTRODUCTION

DRAMs have consistently demonstrated their usefulness in avionics and space systems despite their sensitivity to single event effects (SEE) and total ionizing dose (TID). The DRAM offers a high density of bits due to its simple cell, and error detection and correction methods have become more sophisticated. The low power and high speed of the DRAM also make it very attractive for avionics and space systems. During the last decade, DRAM cells operating at lower voltages have also become smaller, resulting in unprecedented radiation effects and higher sensitivity to previously seen effects. Therefore, careful characterization of high density DRAMs is crucial. This paper outlines a method for using DRAM retention time to characterize the device in terms of TID effects of the whole device as well as single DRAM cells.

Much research has been conducted concerning radiation effects on DRAMs, especially in terms of SEU [1]-[9]. The focus of the research has been directed primarily toward the temporary effects of a SEU; any lasting effects have not been considered. Residual effects can affect the entire device or a single DRAM cell [10]-[11]. Both effects are of equal importance. Where the entire device is concerned, the device behavior of all the cells will reflect a TID effect. Analyzing each cell will yield the individual effect of radiation, especially SEU-inducing radiation. In this paper, the time a DRAM cell requires to lose its programmed value without being refreshed, called the retention time, is examined. This paper examines how radiation affects the retention time of the DRAM in terms of the total dose response of a whole device and then in terms of the effect SEU-inducing ionizing radiation exerts on the retention time of a single DRAM cell [10].

II. DRAM DEVICES

A DRAM cell consists of a capacitor and a transistor. The capacitor stores the bit of information and the transistor isolates the capacitor during non-read or non-write times, which is approximately 99% of the time. A schematic of a typical DRAM memory array is illustrated in Fig. 1 [8]. During this time, the cell experiences subthreshold leakage that causes the DRAM cell to lose its programmed state. Thus, the cell needs to be refreshed, i.e., rewritten, occasionally. If it is not refreshed, the cell will eventually fail to retain its datum. This time to fail should decrease as a function of radiation exposure, and this effect is the foundation of the paper.

An important realization concerning the DRAM cell (shown in Fig. 1) is that half of the cells are in the zero state when programmed, while the other half are in the one state when programmed. Now, since a DRAM can only upset in one direction, a DRAM programmed with all ones or zeros will have about half of the cells vulnerable to SEU. Previous studies have reported an equal rate of both zero-to-one and one-to-zero flips [4], which may indicate equal upset probabilities inherent in both cell types. This is sensible, since both types of bits store charge in a similar manner. Care must be taken to fill the correct pattern into the device to ensure that all cells may be upset during a SEU test.

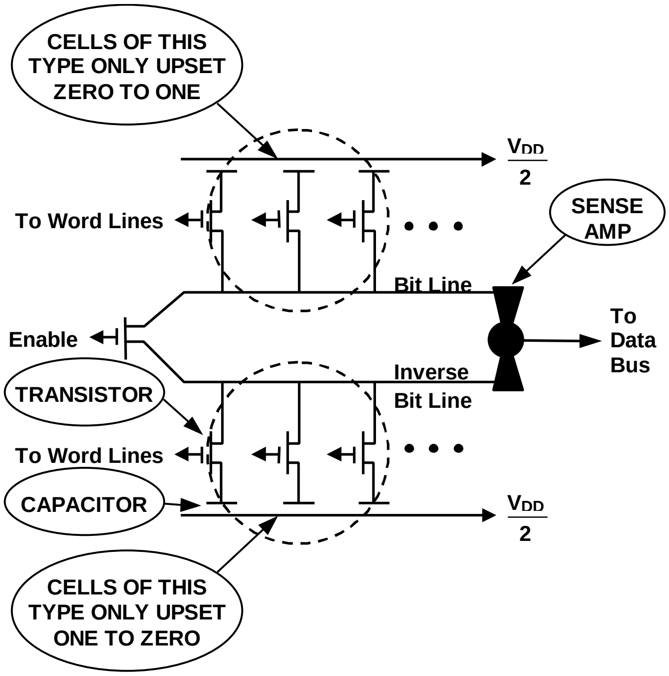


Fig. 1. A DRAM schematic. Note the nature of the DRAM cell pair. Both the bit line and the inverse bit line are held at $V_{DD}/2$ when device is not being read or written, which is over 99% of the time.

III. THEORY AND TEST SETUP

The test setup used in this experiment uses a personal computer to program the DRAM through a dedicated device under test (DUT) board. The DRAM device is programmed per manufacturer specifications. The device is then interrogated to determine the time at which each cell fails to report its programmed state due to leakage. This is called the retention time. In theory, the retention time of the device should be due only to the capacitance of the cell, the availability of minority carriers to cross a reversed-biased junction and discharge the capacitor, resistance of the leakage path through the access transistor, and the level at which the sense amps are set. Given the amount of process variation during manufacture, the distribution of retention times of all of the DRAM cells should have an appreciable variance.

Measuring the retention time for a DRAM is complicated, since the DRAM automatically refreshes the cells after a read. The manufacturer specifies a refresh time of 64ms, which is the maximum time between rewrites that data is guaranteed to remain in the cells without error. Measurement of the retention time of a cell is determined by writing to the DRAM and not accessing the device for the desired amount of time. The device is then readout, and the bits that report an error are recorded. This cycle is then repeated for another desired measurement of the retention time until a curve of bit errors versus time of desired precision is acquired. For this study, the single ion effects were expected to cause a large effect to single DRAM cells. So, the various retention times were measured in geometrical steps, i.e., for each read delay, the next lesser delay is half as much, and the next larger delay is twice as much. These measurements allowed scanning for large effects in addition to reduced accelerator time.

Due to manufacturing variance between DRAM cells, the distribution of retention times across the device will be quite wide. There is also the variance in the retention time that a single DRAM cell will have if the retention time is measured multiple times. The cell variance is expected to be quite small. So, comparing retention times before and after radiation exposures should give an excellent measurement of the radiation effects on DRAM cells. The difference in retention time of each cell reflects the variance in retention time. This fact allows for measurement of the change in retention time that radiation has caused.

Fig. 2 shows this method for a simulated distribution, which plots (dN/dt)/N, where N is the number of cells, as a function of t and the distribution of shift in retention time for no irradiation. The retention time distribution here is assumed to be due solely to the variation in each cell's retention time as opposed to the variance across the device. A large retention time shift in a single DRAM cell, well outside of the distribution, would be the result of a large, rare dose deposition. This method has successfully been used to describe single cell effects and small volume dose, or microdose [12].

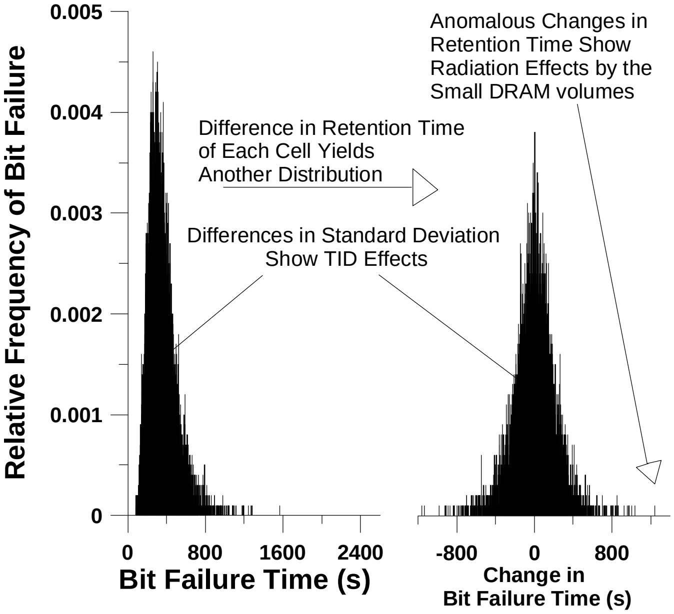


Fig. 2. A simulated DRAM response. The frequency of retention times for all DRAM cells is shown on the left, and the variation of retention time for the cells is shown on the right. The distribution on the right results from the difference in pre- and post-irradiation retention times for each cell in the DRAM. Both dose and microdose effects can be studied from the distribution on the left. Microdose is the deposition of energy in a small (~µm^3) volume.

IV. RESULTS

Several different DRAMs were tested for changes in retention time. Shown below are two Toshiba 16Mb DRAMs. A proton exposure to a Hyundai 64Mb DRAM is also presented for comparison. The devices were used in normal mode with no extra circuitry or modification. The temperature of all devices was held at 40 °C.

A. Statistical Macroscopic Results

Since most of the distribution is due to variance across the device, and not retention time variance, permanent changes in the retention time distribution are due to radiation effects. These results will be very valuable when considering the single cell effects below. These results also show that cells have different susceptibility to damage.

The change in the cumulative number of errors for various gamma exposures is shown in Fig. 3 [11]. Fig. 3 also shows fits for each data set [13]. The radiation source was gamma from the JPL Colbalt-60 room irradiator. The data are fit by the empirical function:

$$N = N_0\left(1-e^{-\left(\frac{t}{t_0}\right)^a}\right)^b , \qquad (1)$$

where t_0, a ,and b are constants. N is the number of errors at time t, and N_0 is the total number of DRAM cells.

Fig. 4 demonstrates a very useful result. Plotted is the normalized retention time needed for one half of the DRAM cells to report an error. This allows a method of equating retention time shift with an average dose per DRAM cell. Fig.

4 is derived by fitting (1) to the data in Fig. 3 and then solving for t, where N= $N_0/2$. The dose that a DRAM cell has received during an SEU event can be determined by using Fig. 4 as a calibration.

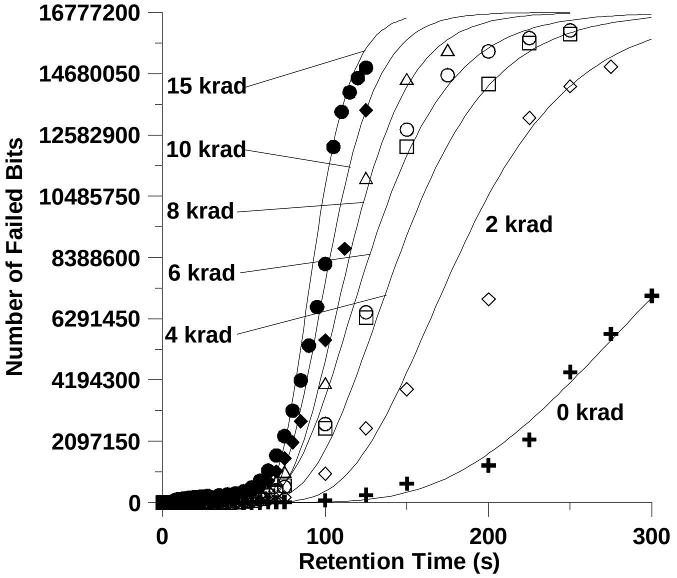


Fig. 3. Retention time of a Toshiba 16 Mb DRAM due to different radiation exposures. The change in the structure of the curves indicates a total dose effect.

The cumulative errors as a function of retention time for heavy ions were measured. Two Toshiba TC51648065APT devices were tested. The results are shown in Figs. 5(a) and 5(b). Before and after exposure to 10^4 210 MeV (11.4 MeV-cm^2/mg) chlorine ions (1.824 rad(Si)), the change in retention time was measured for each cell. Such a small amount of radiation was applied to get meaningful SEU statistics and to observe any early retention time changes. Figs. 5(a) and 5(b) show the cumulative failure of all bits as a function of the retention time. The curve with "1" as a label is a measurement before irradiation. The "2" curve is post-irradiation. The first device is shown in Fig. 5(a). There is significant deviation from the pre-irradiation curve for approximately 0.01% of the bits. These deviations are not present when no radiation has been applied, i.e., the cumulative error distribution is very repeatable. Another device shows similar results, which is shown in Fig. 5(b).

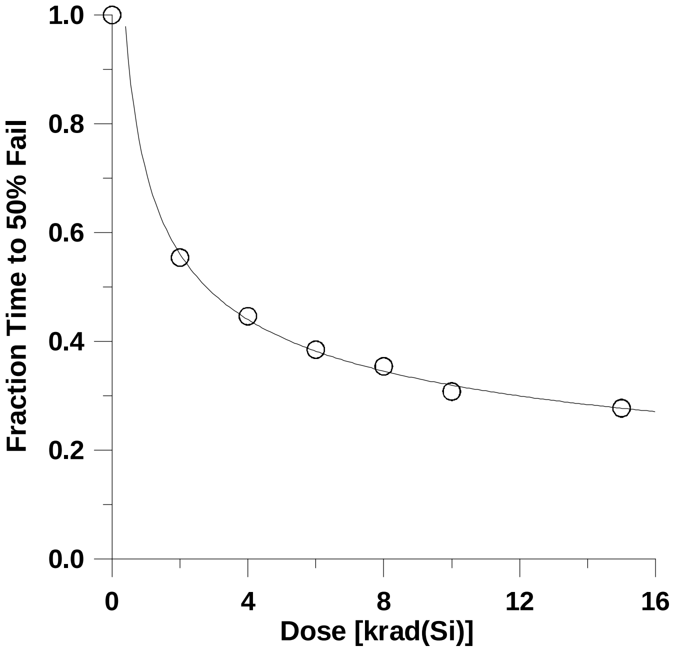
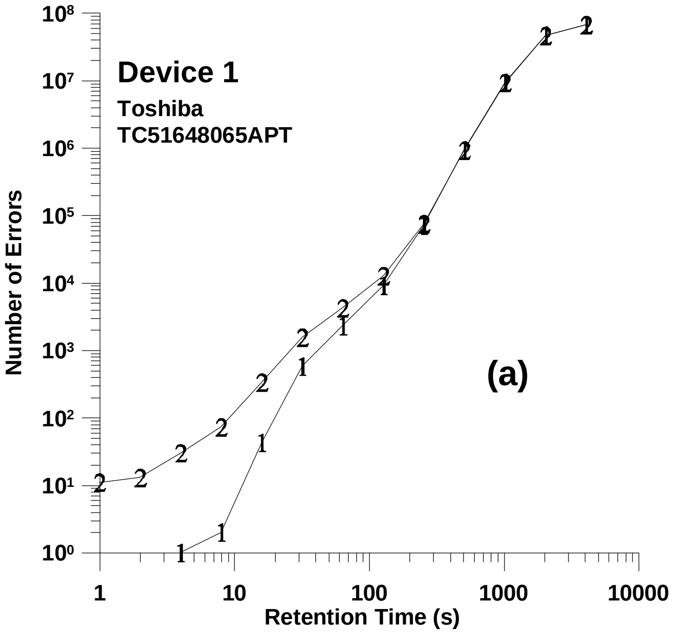


Fig. 4. The retention time required to record 50% errors on the device as a function of dose. This is, in effect, the median change in retention time, which can be used to estimate the dose absorbed by a single DRAM cell. The data obeys a power law fit with an exponent of -0.35.



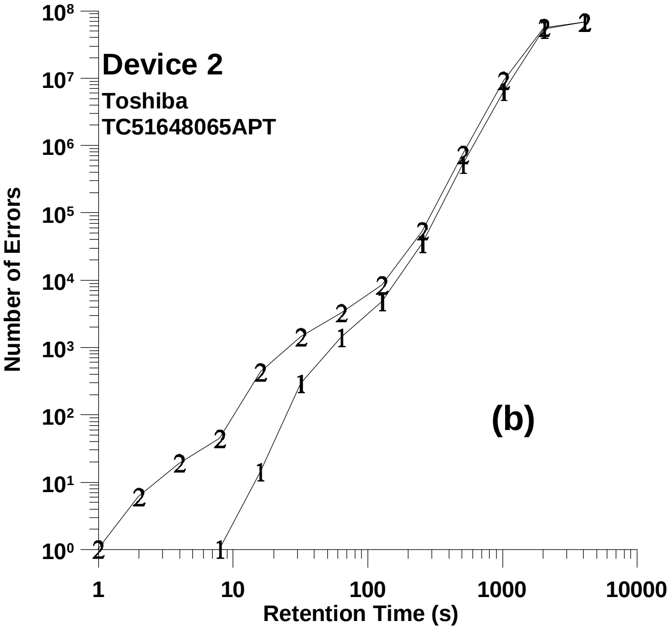


Fig. 5. Total number of errors versus time delay until read for two Toshiba TC51648065APT 16Mb DRAMs. The "1" label signifies data taken before irradiation, and the "2" signifies data taken after irradiation with 10^4 210 MeV (11.4 MeV cm^2/mg) chlorine ions (1.824 rad(Si)). The shift of only 0.01% of the bits to lower retention time signifies the microdose effect. These devices have manufacturer specified retention times of 64 ms.

B. Single Cell Dose Results

Analysis of the retention time for each cell was conducted using two Toshiba TC51648065APT DRAMs. The retention time was measured for each cell before and after exposure to 10^4 11.4 MeV-cm^2/mg chlorine ions. Fig. 6 illustrates the radiation-induced changes in retention time for the 8028 bits that reported an upset (bottom histogram) and 8028 randomly selected non-upset bits (top histogram). Bits that experience no SEUs show no shift. Bits that did report an SEU show a shift toward lower retention times, which implies a large dose to a small volume. In Fig. 6, the abscissas have been altered for ease of viewing. The log of the absolute value of the shift multiplied by the sign of the shift is plotted on the abscissa. The cells which reported zero retention time shift were left at zero. The degeneracy between zero and ln(1) is inconsequential, since very few bits had a one second retention time change. Using Fig. 4 to calibrate, the peak of the distribution (at abscissa coordinate -4) corresponds to a dose of approximately 1 krad(Si) in the small volume that makes up the sensitive portion of the DRAM cell.

Approximately 40% of the upset bits show an appreciable change in retention time from the pre-irradiation measurement. This implies that there may be at least two types of SEUs that effect these DRAMs: those that cause a retention time change, and others that do not. The exponential time steps used in measuring the retention time of the DRAM may mask smaller changes in retention time. More precise retention time measurements will be needed to determine whether or not there are multiple SEU modes. This will be investigated in a later study.

Device 2 demonstrated similar results. Device 2 had 6758 SEUs and is shown in Fig. 6(b). Note that, while there is a significant part-to-part variation in upset susceptibility among the two devices, Device 2 displays shifts in retention time similar to Device 1.

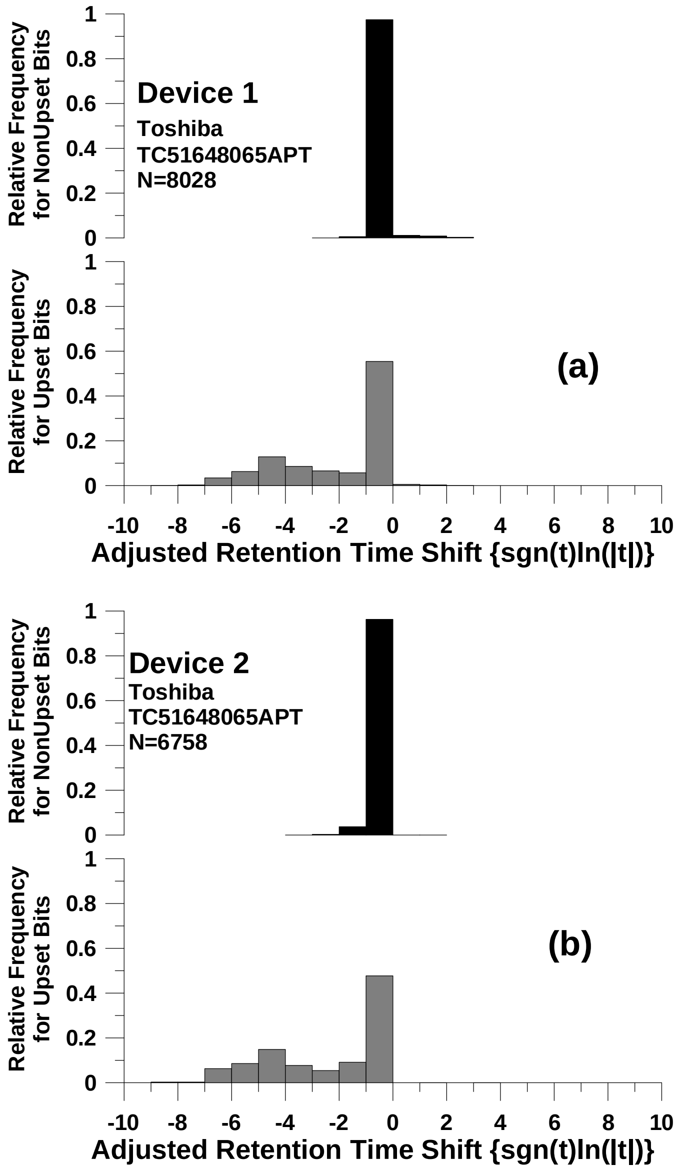


Fig. 6. The change in retention time due to ions for two Toshiba TC51648065APT 16Mb DRAMs. Negative shifts indicate that post-irradiation retention times are shorter. The {sgn(t)ln(|t|)} modification contracts the abscissa for ease of viewing. The sgn function returns the sign of the argument.

Fig. 7 shows a comparison of retention times before and after a proton irradiation. In this case, 2 x10^9 cm^{-2} protons irradiated onto a Hyundai 64Mb DRAM. The upper spectrum shows 1639 randomly selected cells that did not record an upset. There is very little change (<100 s shift to negative values) for most of the bits, while about 10% show a larger negative shift. This spectrum serves as a reference for the upset bits. The spectrum on the bottom shows the change in retention time for the 1639 upset bits. Two important effects are demonstrated. First, most of the upset bits experience a shift in retention time of approximately 200 s. This shift is probably due to the most common upset mechanism. Second, larger changes in the retention time occur for the upsetting case than for the non-upsetting case. This effect is due to the fact that these cells were subjected to much larger proton-induced events that go beyond the 200 s shift seen in the bulk of the upset bits.

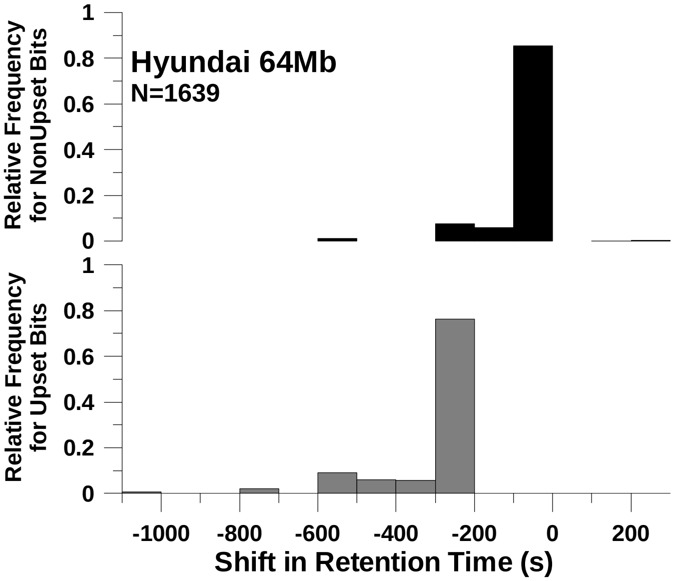


Fig. 7. The change in retention time due to protons for the Hyundai 64Mb DRAM. Negative shifts indicate that post-irradiation retention times are shorter.

VI. CONCLUSION

Taking advantage of the change that ionizing radiation causes in the retention time of DRAM cells has yielded a new analysis of radiation effects on DRAM cells. The changes in retention time can be analyzed for the whole device and for individual cells to extract radiation effects information. Bits that are upset may possess such shortened retention times that they pose a softer upset risk or are susceptible to stuck bits.

In addition, DRAMs that experience stuck bits in space environments may actually possess sufficiently shortened retention times so that their cells immediately drain before they can be refreshed. The data shown here imply that radiation-induced shortening of retention time is not strongly the cause of stuck bits in these devices. Newer DRAM technologies may be more susceptible to stuck bit behavior due to greatly decreased retention times. More precise measurements of the energy deposited to the DRAM sensitive volume are being conducted.

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