Directional Dependence of SEU Cross Section for a High-Density SDRAM

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ABSTRACT

SEU cross section data for a highly scaled SDRAM show that tilting the ion beam causes the effective LET to decrease instead of increase. A format for presenting test data is suggested.

I. INTRODUCTION

To accurately predict SEU rates for DRAMS in space environments, the cross section’s angular dependence must be determined. Using the terminology of the RPP model traditionally used for rate calculations [1], the ratio of the RPP thickness to each lateral dimension must be known. It has been determined from simulations [2],[3] and from experimental measurements [4] that diffusion is the primary charge-collection mechanism that leads to upsets in slow devices such as DRAMs. In contrast, the RPP model is a geometric model that can be used as a fitting tool but is not a literal description of charge-collection physics when diffusion is important. Therefore, RPP dimensions for rate calculations may require measuring the directional dependence of the cross section and selecting parameters to fit the data, hence a complete set of measurements are needed for accurate predictions. This paper investigates the directional dependence for one highly-scaled device; the Samsung K4S510832M 512 Mbit SDRAM, in addition to providing data on this state-of-the-art device. It will be seen that this device does not have the behavior that is typical in older generations, and that changes are needed in the way SEU test data are evaluated.

The common practice for presenting SEU test data is to convert data measured at various angles via an assumed cosine law. When the cosine law is successful, the converted data points lie on a single curve, so all points can be shown in one plot. Traditional methods for calculating SEU rates recognize that the cosine law has limitations, so the more versatile RPP model is used (the appropriate RPP thickness is typically an educated guess). The inconsistency between the cosine law for data presentation versus the RPP model for rate calculations can be excused if test conditions are such that the cosine law is an adequate approximation over the range of tested conditions. In some devices, the cosine law is an adequate approximation if the tilt angle is suitably restricted (e.g., to not exceed 60°). However, extreme cosine-law failures are becoming increasingly prevalent as device technology advances, so it is becoming increasingly important that directional dependencies be measured. As seen in the next section, the Samsung K4S510832M 512 Mbit SDRAM is an example in which cosine-law failure is so extreme that it becomes necessary to include measured directional effects in data presentation as well as in rate calculations.

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II. CROSS SECTION DATA

SEU data discussed in this section were taken from the Samsung K4S510832M 512 Mbit SDRAM at the Lawrence Berkeley National Laboratory cyclotron. The devices were de-packaged and rebonded so the ion beam can reach the active layer without degradation from packaging material or metal lead frames. The tests varied the angle of the beam relative to the device in addition to varying ion LET. All data presented here were obtained from angles at which the entire device was exposed to the beam. Also, the full paper will present arguments and additional data (not included here) indicating that the charge-collection depth in this device is shallow enough so that the observed directional dependencies of the cross section are meaningful and not an artifact of test-ion range limitations.

Cross sections versus LET are plotted in the traditional cosine-law format in Fig. 1. In the notation used here, the cross section \( \sigma \) is the directional cross section. It is experimentally defined as the number of SEU counts divided by beam fluence, with fluence measured in a plane perpendicular to the beam (as opposed to the device plane). This is the cross section that is most convenient when calculating the SEU rate for a "black box", i.e., when there is no physical model but, instead, the cross section is measured for all angles and LETs. The tilt angle is \( \theta \) and the azimuth angle is \( \varphi \). The cosine-law plotting format divides the directional cross section by \( \cos \theta \) to obtain an area in the device plane whose projection in the beam direction equals the measured cross section. The cosine-law format also divides the ion LET \( L \) by \( \cos \theta \) to obtain an "effective LET". This is the format used in Fig. 1, but the extreme scatter in the figure indicates that this format is not useful for the device considered here, even though it works well for some of the older generation devices.

A more informative plot shows several curves corresponding to different tilt angles. This is done in Fig. 2, which plots directional cross section versus ion LET for each of several directions (data are shown for only one azimuth angle to reduce clutter but the full paper will show all data points).

A more convenient plotting format has the same objective (to place all points on a single curve) as the cosine-law format, but is better able to accomplish this objective via additional flexibility. This is the alpha-law format [5]. The general form of the alpha law is

\[
\sigma(L, \theta, \varphi) = \alpha(\theta, \varphi) \cdot \sigma_N(L/\alpha(\theta, \varphi))
\]

where \( \sigma_N \) is the normal-incident cross section and \( \alpha(\theta,\varphi) \) is a function of the incident angles. The alpha law has the same form as the cosine law except that \( \cos \theta \) is replaced by \( \alpha(\theta,\varphi) \). The alpha law can be derived from the sensitive volume model if the sensitive volumes are ellipsoids (like RPPs but with rounded corners) [5]. In this case, \( \alpha \) is given by

\[
\alpha(\theta, \varphi) = [(A^2 \cos^2 \varphi + B^2 \sin^2 \varphi) \sin^2 \theta + \cos^2 \theta]^{1/2}
\]

where A and B are fitting parameters. For a geometric interpretation, let X, Y, and Z denote the lengths of the three ellipsoids axis, with the third axis perpendicular to the device. Then \( A=Z/X \) and \( B=Z/Y \). The cosine law is obtained when \( A=B=0 \) (the ellipsoid is a flat disc) while an isotropic cross section is obtained when \( A=B=1 \) (the ellipsoid is a sphere). A more general case that also leads to the same pair of equations (1) and (2) is that in which there is a charge-collection efficiency function \( \Omega(x,y,z) \) having the property that the family of constant-\( \Omega \) surfaces can be adequately fit by a family of concentric ellipsoids [5].

The data in Fig. 1 are plotted in the alpha-law format in Fig. 3. The full paper will include an algorithm for selecting fitting parameters that is less cumbersome and less subjective than the
algorithm illustrated in [5]. The alpha law does not give a perfect fit, so the points do not exactly line up on a single curve, but the scatter is much less than in Fig. 1. To the extent that the points can be represented by a single curve, this curve represents the LET dependence of the cross section, while the directional dependence of the cross section is implicitly implied by the fitting parameters A and B. The curve shown in Fig. 3 was selected to envelope most of the scatter for a slightly conservative representation of the data. It is a simple fit because there are only two adjustable parameters (the full paper will give the equation and a more detailed discussion).

III. DISCUSSION OF THE DATA

Note that the curves in Fig. 2 come together (the cross section becomes isotropic) at large LET. This is consistent with a theoretical diffusion analysis [6], which predicts that the curves should come together at sufficiently large LET. However, a characteristic not shared by some older device technologies is the systematic shifts in the curves towards the right with increasing tilt angle. A given ion LET is less able to produce SEUs at the larger tilt angles. This is opposite to the usual trend in older device technologies, in which an increase in tilt angle increases the effective LET and causes an ion to be more capable of causing SEUs. For the device in Fig. 2, even at small tilt angles, an increase in tilt angle decreases the effective LET.

The same conclusions, but with some additional insight, can be obtained from the A and B parameters in Fig. 3. Although the alpha law applies to a charge-collection model that is more general than the sensitive volume model, the sensitive volume model is still useful for visualization purposes, so we will assume that it applies for the purpose of this discussion (the alpha law is exact if the sensitive volumes are ellipsoids). The fact that the A and B parameters are greater than 1 implies that the sensitive volume is taller than it is wide, which explains why a normal-incident beam is more capable of creating SEUs than a tilted beam. A possible explanation for the sensitive volume aspect ratio is the use of trench isolation that causes the capacitors to have high aspect ratios. Trench isolation might also explain the scarcity of multiple-bit upsets. The saturation cross section is on the order of the device area, indicating a low multiplicity factor (average number of cells upset by one ion hit). In contrast, some older DRAMs (e.g., the OKI device discussed in [6]) show large multiplicity factors.

The type of plot illustrated in Fig. 3 can be used to define some terminology. It was previously stated, when discussing Fig. 2, that the effective LET decreases with increasing tilt angle. This statement was not rigorous, because effective LET was not precisely defined, but the intended meaning is that a given ion LET is less able to produce SEUs at the larger tilt angles. The statement becomes rigorous if effective LET is defined to be L/α(θ,φ). With this definition, it is easy to show from (2) that effective LET decreases with increasing tilt angle if A and B exceed 1 (the sensitive volume is taller than it is wide), but increases with increasing tilt angle if A and B are less than 1 (the sensitive volume is wider than it is tall).

IV. CONCLUSIONS

It is well known that the cosine law becomes invalid at sufficiently large tilt angles, but the test data presented here for a highly scaled device show that cosine-law failure can occur in some devices even at small angles. In particular, tilting the ion beam can cause the effective LET to decrease instead of increase, compared to the normal-incident case. Using sensitive volume model terminology, the sensitive volume is taller than it is wide. A possible explanation is the use of trench isolation, which causes the capacitors to have high aspect ratios. Regardless of the explanation, angles and LET should both be varied in order to obtain a complete set of data for such devices. Furthermore, cross section data should be presented in a way that shows the directional dependence as well as the LET dependence. One option is the alpha-law plotting.
format, which is very similar to the traditional cosine-law format and can be used to define an effective LET. It is believed that this practice will become increasingly important as device technology advances.

REFERENCES