Automating the Modeling of the SEE Cross Section's Angular Dependence

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I. INTRODUCTION

The upset cross section for most storage and logical devices exhibits a strong dependence on the direction of the momentum vector of the bombarding particle. The resulting upset rate in a space environment can be under-predicted by several orders of magnitude if this dependence is not explicitly made in the rate calculation. Because of the difficulties associated with completely measuring the cross section as a function linear energy transfer (LET) and beam orientation, typically only a few off-normal measurements are made, and models are used to extrapolate results to all angles. Currently, the two most popular models are the Rectangular Parallel Piped (RPP) [1] and the cosine law, which reproduces the RPP results for an infinite domino-like slab.

Typically, all SEU cross section data is transformed (via an assumed transformation law) to a coordinate system that is natural to the device under test (DUT), i.e. bombarding momentum is perpendicular to the device plane. A necessary but insufficient condition for the transformation to be valid for a particular device is that the transformed data should lie on a single `smooth' curve (neglecting statistical scatter). If the transformed data does imply an unambiguous smooth curve, the inverse transform can be used to predict the cross section at all bombarding orientations and beam LETs. Implicit in this methodology is that the applicability of the effective LET concept. That is beam orientation and beam LET are not independent variables, and thus do not form an orthonormal basis for the cross section function, but instead are manifestations of the same environmental variable. This notion stems from the definition of LET and geometrical considerations.

In practice, the cosine law is typically used to transform angled data to the normal plane, and a parameterized function (i.e. Weibull) is fit to the data. To perform the solid angle integration for the rate calculations, the ratio of the RPP thickness to each lateral dimension is assumed, and the curve is transformed as a function of beam angle via the RPP model. For particle beams with appropriate range, this phenomological method has met with much success in not only generating smooth normal incident curves, but also determining verifiable upset rates in space for certain devices. However, the RPP model is a geometric model that can only be used as a fitting tool and is not a literal description of charge-collection physics when diffusion is important. 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. With shrinking feature size and increasing device complexity, the limitations of this box like charge collection modeling is apparent. Even as earlier at 1987 [7], this approach was known to be limited.

Edmonds [5] has introduced the alpha law, which is a more generalized transformation law, and can be derived from the sensitive volume model if the sensitive volumes are ellipsoids (like RPPs but with rounded corners). The alpha law has the same form as the cosine law except that $\cos\theta$ is replaced by $\alpha(\theta,\varphi)$, i.e.

$$\sigma(L, \theta, \varphi) = \alpha(\theta, \varphi)\ \sigma_N(L/\alpha(\theta, \varphi)) \tag{1}$$

where σ_N is the normal-incident cross section and $\alpha(\theta,\varphi)$ is a function of the incident angles,

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

One sees immediately that the transformation is parameterized by A and B. Note that for the special case of A=B=0, the cosine law is reproduced, thus the cosine law is a special case of the alpha law.

In practice, the values for A and B are chosen so that the `smoothest' normal curve is produced. In [5], Edmonds reports a DRAM data set where the cosine law produces a very scattered plot, i.e. the angular response of this device cannot be modeled with the cosine law, and thus it cannot be used to calculate a realistic upset rate. He also shows that for appropriate choices of A and B, a smooth curve results. A parameterized curve is fit to the transformed data, and the inverse alpha transformation is used to determine the cross section for all flux orientations.

The alpha law has several advantages over the community entrenched transformations: (1) it is derived from charge collection physics, and thus more closely models reality, (2) is more general than the RPP, but will reproduce RPP results when applicable, (3) no arbitrary choice for the RPP aspect ratio is needed to perform upset rate calculations, (4) can be used to predict the angular response for devices where the cosine law fails, and (5) it predicts the possibility of an azimuthal dependence for the cross section. This dependence has been experimentally observed for a number of devices [6], and cannot be modeled with the cosine law. Note that point (3) is significant because the upset rate for some devices is sensitive to this choice by an order of magnitude. Point (4) is becoming increasing significant because with modern feature sizes and architectures, more and more devices are being tested where the cosine law fails.

The alpha law as presented in [5] is somewhat cumbersome to use in that no rigorous technique existed to determine the values of A and B. Instead, the author picked values for A and B, performed the parameterized transformation, and plotted the resulting data set. The author performed this process for many values of A and B, while judging the smoothness of each transformed data set by inspection of the plot, and the values that resulted in the smoothest transformation were chosen (a very subjective decision). For the alpha law to be a viable alternative to the cosine law, it is clear that a method to unambiguously determine the appropriate values for a given device must be developed.

This paper presents an algorithm that automates the determination of A and B, while also eliminating the subjectiveness associated with determining the smoothness of plots. Software has been developed that takes raw accelerator data as input and finds the appropriate choices of A and B that result in the smoothest transformation. The software also has the capability to integrate the resulting cross section over solid angle and also, if given the environment as an input, perform the full rate calculation. With this fully automated implementation of the alpha law, a sophisticated SEE data analysis can be performed in real time as accelerator data is acquired. It must be reiterated that this analysis is much more applicable to modern day devices than the RPP due to reason (1)-(5).

As a test case to demonstrate the usefulness of this tool, this work also presents measurements of the upset cross section of a highly-scaled device; the Samsung K4S510832M 512 Mbit SDRAM. The data set clearly violates the cosine law and thus the alpha law is essential to predict reliable upset rates. The software package is used to analyze the data that was taken and the results are given.

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 σ 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). The extreme scatter in the figure indicates the angular dependence predicted by the cosine law does not apply to this device, thus a more sophisticated model (the alpha law) is need to model the angular response of the device.

Fig 2 shows the resulting alpha law fit. The software developed for this work was used to determine the optimum values of A and B: 5 and 3 respectively. For a geometric interpretation of A and B, 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. Note that an isotropic cross section is obtained when A=B=1 (the ellipsoid is a sphere) and the cosine law is reproduced for the choices of A=B=0. 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-Ω surfaces can be adequately fit by a family of concentric ellipsoids [5].

The alpha law does not give a perfect fit, so the points do not exactly line up on a single curve (they shouldn't due to statistical scatter), 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 (at normal incidence), while the directional dependence of the cross section is implicitly implied by the fitting parameters A and B. The curve shown in Fig. 2 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). The full paper will also discuss the algorithm used to determine A and B, and will also provide the source code for the fully automated alpha law including the ability to determine space upset rates.

III. DISCUSSION OF THE DATA

Note the implication for the parameter choices of A,B>1: 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. Indeed, this effect is seen in this and other data sets.

This result is unexpected to a many in the community, thus some physical insight is useful. 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. 2 can be used to define some terminology. According to the alpha with choices of A and B >1, the effective LET decreases with increasing tilt angle (effective LET is defined to be $L/\alpha(\theta,\varphi)$), i.e. a given ion LET is less able to produce SEUs at the larger tilt angles. Simply stated, the 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 (and [5]) 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. The alpha law is known to have several advantages over the cosine law (reasons (1)-(5)).

For the first time, this work (the full paper) demonstrates a software tool that can be used to automate the somewhat cumbersome alpha law. This is a very valuable tool to the experimentalist who is accustomed to applying the cosine law to accelerator data, because now the more sophisticated alpha law can be applied with the same level of simplicity. The software will also allow for the solid angle integration and upset rate calculation, thus the alpha law is now as accessible as the more traditional techniques of interpreting angular data and performing rate calculations. Because of these reasons, and the fact that the cosine law failures will continue to be more extreme as device technology advances, it is believed by the authors the alpha law will become increasingly more important to the SEE community.

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