# The Contribution of Diffusion to Device Upset Cross Sections

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**A novel technique, incorporating carrier recombination, for determining the charge collection efficiency function, $\Omega_\tau(\vec{x})$, is presented and applied to a realistic, 3-D, memory device, to obtain the upset cross section, $\sigma$, as a function of LET and orientation of incidence. The theoretical predictions are shown to exhibit a high level of agreement with experimental measurements.**

## 1 Introduction

Historically, many of the attempts to predict heavy ion-induced upset cross sections, $\sigma$, have been based solely on geometrical considerations, with minimal input from semiconductor physics. The Rectangular Parallelepiped (RPP) [1] and its more sophisticated counterpart, the Heavy Ion Cross Section for Single Event Upset (HICUP) [2, 3] have been popular constructs used to model $\sigma$ and calculate device upset rates for many years. Although these approaches have been successful in replicating experimental measurements when model parameters are selected to fit data, the limited physical input leaves their applicability to future volatile memory devices somewhat limited.

In recent years, efforts to construct charge collection models governed by the charge transport equations incorporating carrier recombination and drift/diffusion have been undertaken by various members of the SEE community. Due to the wide availability of sophisticated packages that employ finite element analysis to solve the Poisson and continuity equations, much has been learned regarding the evolution of injected charge in a device via computer simulations [4, 5]. However, full 3-D simulation codes are computationally intensive, so a great deal of effort and machine time are needed to predict upset cross section as a function of ion LET and incident angle, even for simple, single or double junction devices. The computational intensity for more complex devices, such as DRAMs, that contain millions of cells and have the property that charge can travel great distances from an ion track to upset a particular cell, can be overwhelming.

Other authors such as Kirkpatrick [11], Wouters [12], Smith et al. [7], and Edmonds [8, 9], used a more analytic approach intended for those cases in which diffusion is believed to be the dominant charge transport mechanism. However, the first three authors assumed Dirichlet-type boundary conditions on the entire upper device plane (the cell density is large enough for adjacent cells to share boundaries). Edmonds used the more versatile mixed-type boundary conditions, but his treatment still contained unrealistic simplifications (an entire array of cells is replaced by several types of regions defined by concentric rings). Also, while Edmonds treated recombination in the theory, [8], this was not included in the numerical results. A more recent paper [10] removes these limitations only if the reader can supply information that is difficult to obtain and is unique to the geometry of interest. The present paper is the first to use mixed boundary conditions that give a literal representation of a large array of cells of arbitrary aspect ratio and spacings. Furthermore, recombination is included in the numerical results. In this summary, the predicted dependence of the cross section on LET is shown to agree with experimental data, even for large $L$, In the final paper, the dependence on orientation of the ion strike, as well as device geometry and other input parameters will be fully investigated.

Like the earlier analytic treatments discussed above, it is assumed that charge transport is governed by diffusion. It has been known for some time that diffusion can transport charge over large distances in DRAMs [6]. A more recent comparison between diffusion calculations and simulation results (drift/diffusion equations) indicates that diffusion is also important to a so-called "prompt" component of collected charge [10]. The charge-collection time is assumed in the present work to be effectively infinite, so the applicability of this work is somewhat limited. A notable example in which this work is believed to be relevant is the DRAM.

It has been shown in [8] that all information regarding the ability of a DRAM cell to collect charge,

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via diffusion, over a long enough period of time, is contained within the cell's charge collection efficiency function, $\Omega_\tau(\vec{x})$. This function is a scalar potential that depends only on the device boundaries, and lifetime of the injected carriers, $\tau$. Once determined for a particular geometry and $\tau$, $\Omega_\tau(\vec{x})$ can be used to calculate $q_o$ for an arbitrary charge density, $\xi(\vec{x}, t)$,

$$q_o = \int \Omega_\tau(\vec{x})\, \xi(\vec{x}, t=0)\, d^3x. \tag{1}$$

The upset cross section of a single node is the area contained within a particular equipotential surface of $q_o$ lying on the upper plane of the device. Knowledge of $q_o$'s sensitivity to the position, orientation, and LET of a heavy ion strike, might help explain various experimental observations such as: corrections to the standard Weibull curve, deviations from the cosine law [1], and the strong azimuthal dependence exhibited by some devices [13]. Indeed, it is demonstrated in [14] that, by assuming the equipotential surfaces of $\Omega_\tau(\vec{x})$ are ellipsoids, the alpha law provides a generalized angular dependence for the cross section, which reduces to the azimuthal-independent cosine law as a special case.

## 2 The Diffusion Problem

As shown in reference [8], $\Omega_\tau(\vec{x})$ is defined to satisfy

$$\mathcal{L}\Omega_\tau(\vec{x}) = 0, \tag{2}$$

where $\mathcal{L}$ is the modified Helmholtz operator, $(\nabla^2 - \kappa^2)$, $\kappa^2 = \tau^{-1}D^{-1}$, and $D$ is the diffusion coefficient.

The device under consideration is modeled as a silicon volume, occupying the half space $z \leq 0$, with the $z = 0$ plane coinciding with the upper boundary of the device where the ion strike enters the sensitive volume. This plane contains an infinite rectangular array of sinks, each representing the area of charge collection for a particular cell. The sinks are labeled $S_0, S_1, ...$, with the center of the sink of interest, $S_0$, being placed at the origin (see Figure 1). The sinks have dimensions of $\{2a, 2b\}$ in the $\{x, y\}$ directions and are separated by the corresponding distances $\{\alpha, \beta\}$. The lack of a lower boundary on the device is justified if $\Omega_\tau \to 0$ for some $z \ll Z$, where $Z$ is the substrate thickness. For the devices under study, this is a realistic simplification. As seen in equation 3, the boundary conditions on the sinks are of the Dirichlet type, while the areas between sinks are of the Neumann type.

$$\begin{aligned} \Omega_\tau(\vec{x} \in S_0) &= 1 \\ \Omega_\tau(\vec{x} \in S_i \notin S_0) &= 0 \\ \frac{\partial \Omega_\tau}{\partial \hat{n}}(\vec{x} \notin S_i) &= 0. \end{aligned} \tag{3}$$

The presence of the mixed boundary conditions complicates the solution to equation 2, and instead we choose to approximate $\Omega_\tau(\vec{x})$, with a series solution, $\Psi_\tau(\vec{x})$,

$$\Psi_\tau(\vec{x}) = \sum_i \sigma_i \psi_i(\vec{x}), \tag{4}$$

where the summation is over all sinks, and $\psi_i(\vec{x})$ is the propagator integral for the modified Helmholtz equation,

$$\psi_i(\vec{x}) = \frac{1}{4\pi} \oint_{S_i'} dx'dy' \frac{\exp\left[-\kappa\sqrt{(x-x')^2 + (y-y')^2 + z^2}\right]}{\sqrt{(x-x')^2 + (y-y')^2 + z^2}}. \tag{5}$$

Note that $\Psi_\tau(\vec{x})$ exactly solves equation 2, and is constrained by the Neumann conditions. However, the choice of the expansion coefficients, $\sigma_i$, which have the physical interpretation of the 'charge' densities that set up the collection efficiency 'field', determines how well the Dirichlet conditions are satisfied, and thus how accurate the approximation is.

In Figure 1, a $5 \times 5$ grid is shown; however, for computations, a $7 \times 7$ array is used. The grid size can be extended to an arbitrary size, however 49 terms is adequate to ensure series convergence. The optimal expansion coefficients are found via the calculus of variations, however, due to space limitations of this summary, the full analysis will be presented in the final paper only.

## 3 Results

To demonstrate the applicability of $\Psi_\tau(\vec{x})$, we arbitrarily set $a = b = \alpha = \beta = D = 1$ and $\kappa = 0.1$, however, the sensitivity to these parameters will be addressed in the final paper. Figure 2 shows equipotential surfaces of $\Psi_\tau(\vec{x})$ on the upper boundary of the device. Note the contour superimposed on $S_0$ has a value of 1, while the contours superimposed on the other sinks have values close to 0, and the other contours lie between 0 and 1, thus the Dirichlet conditions of equation 3 are closely approximated.

To investigate the behavior of $\Psi_\tau(\vec{x})$ within the device, Figure 3 displays the contours of the $y = 0$ plane. Note the normal derivative vanishes deep within the device, justifying the absence of a lower boundary. This figure should be compared with those in reference [8]

The total charge collected via diffusion from an ion of LET$= L$ that strikes the device on the upper plane with coordinates, $x, y$, at an orientation of $\theta, \phi$ is

$$q_o(x, y, \theta, \phi, L) = L \sum_i \sigma_i \int_0^\infty \psi(x + \lambda \sin\theta \cos\phi,$$

$$y + \lambda \sin\theta \sin\phi, -\lambda \cos\theta) d\lambda. \quad (6)$$

Figure 4 shows a plot of the charge collected from normally incident ions, i.e. $\theta = \phi = 0$, and $L = 1$. The cell upset cross section is the area contained in the contour defined by $q_o = q_c$, where $q_c$ is the critical charge needed to upset the cell. Note, this definition of $\sigma_0$ is equivalent to the area of the $q_o$ surface projected onto the $z = q_c$ plane. Since the goal of these studies is not to determine absolute cross sections, but to characterize the behavior of $\sigma_0$ as a function of $\theta$, $\phi$, and $L$, an exact value of $q_c$ is not required. The cross section scales with the area contained in an arbitrary $q_0$ contour. Therefore, this dependence can be established by observing the effects these variables have on a particular contour.

A group of normal incidence ($\theta = \phi = 0$) contours are shown in Figure 5 ($L = 1$). The contours are mapped to upset cross sections (assuming an arbitrary $q_c$), and the resulting $\sigma$ vs. LET curve is given in Figure 6. In order to provide a comparison between the predictions of diffusion theory with experimental observations, measurements of $\sigma$ (taken with a normally incident beam) for the Oki MSM514400 4 Mb DRAMs [13] are included with the figure. Note the high degree of consistency between the experimental measurements and theory, thus providing further evidence that, at least in some devices, diffusion plays an important role in their response to radiation fields.

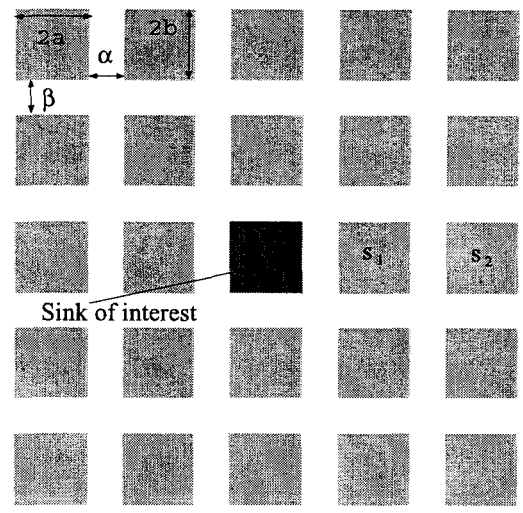


Figure 1: The upper surface ($z = 0$) of a memory device, covered by an infinite rectangular array of carrier sinks, labeled $S_0$, $S_1$, $S_2$, etc. Note the sink of interest, $S_0$, is located at the origin. The sinks have dimensions of $a$ and $b$ along the $x$ and $y$ axis, with spacings of $\alpha$ and $\beta$. The $x$ axis lies along the horizontal, and the $y$ along the vertical.

## 4 Discussion

It is useful to compare the curve in Figure 6 with a result reported in [13], which uses the simpler concentric ring geometry and no carrier recombination. That work found for large $L$ ($L > 35$ MeV-cm$^2$/mg), $\sigma$ varies as $L^2$, and not $L$, as observed both experimentally and predicted by the solution of equation 2 presented here. The inclusion of carrier recombination and a more realistic 3-D geometry provides a stronger connection to real-world devices, thus establishing the significance of this work.

This summary presents a method to obtain the charge collection efficiency function for a realistic 3-D device with finite carrier lifetimes. It also demonstrates how this function can be employed to obtain the upset cross section for a single memory node. The device cross section is simply the sum of all nodes, via the principle of super-position. A comparison between normally incident measurements, and the predicted dependence of $\sigma$ on ion LET, verifies the importance of diffusion with regard to SEUs. The final paper will explore the cross section's sensitivity to the orientation of the incoming particle, i.e. $\theta$ and $\phi$, as well as the device geometry and values of the diffusion constant and carrier lifetime. The orientation predictions will be compared to various models, such as the alpha law[14], and the modified cosine-law [1]. In addition, the studies presented in the final paper will not be constrained by the use of a completely symmetric device, i.e. $a \neq b$, and $\alpha \neq \beta$.

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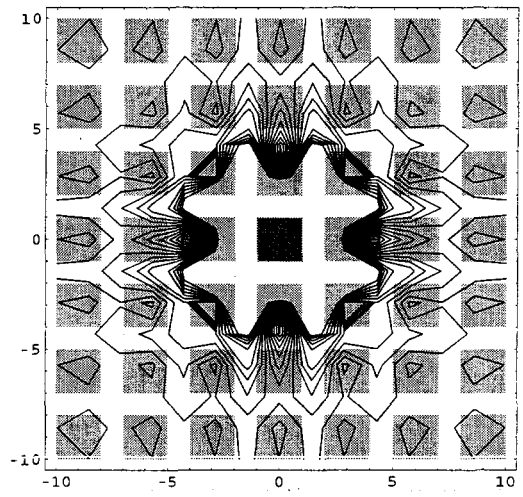


Figure 2: Equipotential surfaces of $\Psi_\tau(\vec{x})$ on the $z = 0$ plane. The equipotential surface on $S_0$ is equal to 1, while the surfaces on the other sinks have values close to 0. The $x$ axis lies along the horizontal, and the $y$ along the vertical.

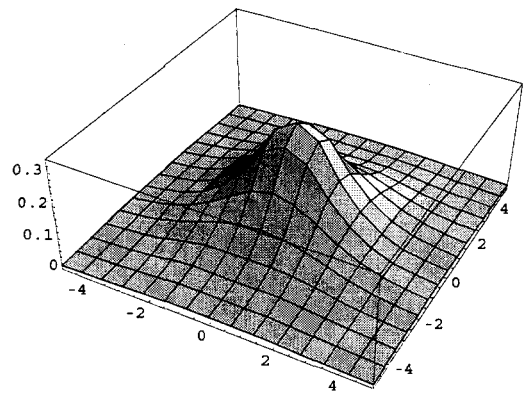


Figure 4: Total charge collected via diffusion as a function of the location $(x, y)$ of a normal incident ion with $L = 1$. Note that maximum amount of charge corresponds to a strike in the middle of the node of interest.

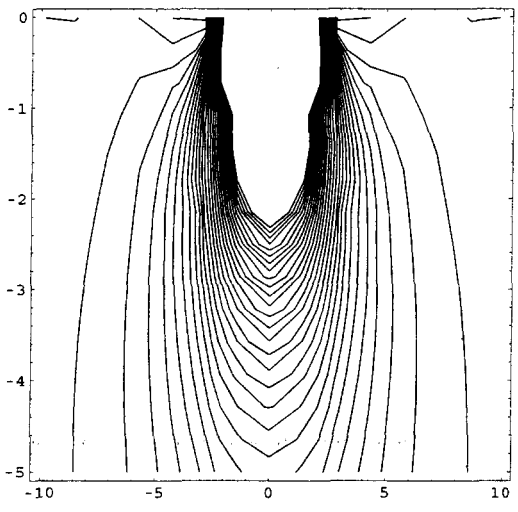


Figure 3: Equipotential surfaces of $\Psi_\tau(\vec{x})$ on the $y = 0$ plane. The $x$ axis lies along the horizontal, and the $z$ along the vertical. Note, the smaller the circumference of a contour, the larger the value.

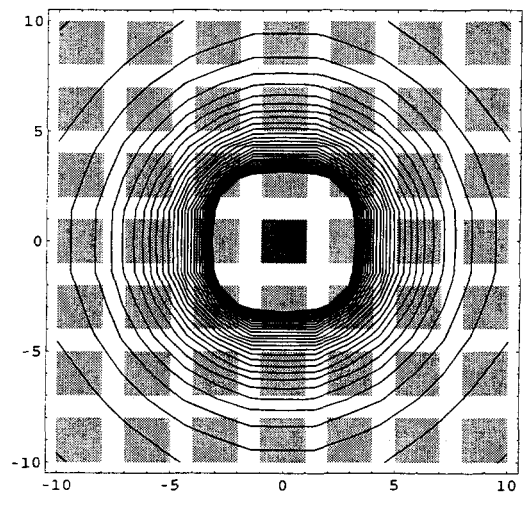


Figure 5: The corresponding contours from Figure 4, projected onto the top of the device. The area defined by the $q_c$ contour is the upset cross section for $S_0$.

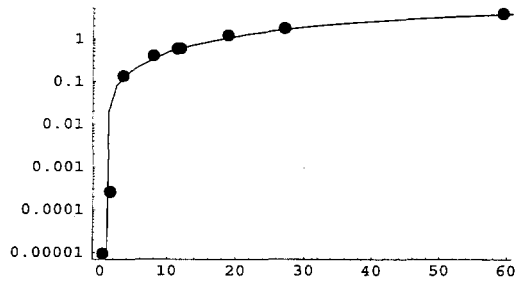


Figure 6: The $\sigma$ vs. LET curve generated by the solution of $\Omega_\tau(\vec{x})$ presented here, along with experimental measurements of $\sigma$ for the Oki MSM514400 4 Mb DRAMs [13], made with a normal incident beam. The $y$-axis unit is $cm^2$, while the $x$-axis is MeV-$cm^2$/mg. Note the exceptional agreement between the experimental data and theory. The theory curve was normalized to the data by an appropriate choice of $q_c$.


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