THE IMPACT OF DELTA-RAYS ON SINGLE-EVENT UPSETS IN HIGHLY SCALED SOI SRAMs

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CHAPTER I

INTRODUCTION

Orbiting spacecraft experience harsh radiation environments that may affect microelectronics in undesirable ways. Ionizing radiation interacts with microelectronics in a variety of ways. One such effect is known as single event effects (SEEs), which is the response of semiconductor device to a single ionizing particle event. Ensuring the integrity of scientific data in harsh radiation environments is critical for the success of missions that require recording and storing large volumes of data. A single event upset (SEU) is an erroneous change in the state of the memory cell. The radiation effects community has developed many experimental and simulation based techniques to determine the sensitivity of memory cells to SEUs.

The role of ion track structure has been a concern in the SEEs community for more than twenty years [1]. Linear energy transfer (LET), the rate of energy lost by the incident ion per unit path length within a material, has been used to relate the space environment to the ground test environment and has been the traditional metric for much of SEE analysis. In more recent years, additional physical mechanisms, for example SEUs resulting from proton direct ionization and nuclear reactions, have been required to describe the conventional cross section versus LET curves obtained by ground based experiments [2], [3]. These trends suggest that technology nodes are becoming sensitive to direct ionization and effects from secondary particles produced by the incident particle's track structure.

Silicon-on-Insulator (SOI) technology has long been advantageous in SEE mitigation due to its small active device area and isolating buried oxide layer (BOX). However, these benefits are

not without cost, as the threshold LET, the LET at which saturation occurs in the upset cross section, for SOI technologies is typically lower than equivalent bulk technologies. With memory cells becoming increasingly sensitive to effects from ionizing particle events, there is concern about the contribution from secondary particles related to track structure of the incident heavy ion. Energetic secondary electrons, δ -rays, are frequently generated in ionizing radiation events. These δ -rays undergo scattering events resulting in localized charge generation comparable to the critical charge of modern SOI technology nodes.

In this work, we use Monte-Carlo radiation transport simulations to evaluate the impact of δ -rays on highly scaled silicon-on-insulator (SOI) technologies. A 22 nm SOI SRAM [23] is used to estimate the geometry and critical charge. Results suggest that long-range δ -rays can deposit sufficient energy to cause single event upsets (SEUs) in SRAM cells separated by many micrometers. We discuss the implications of δ -ray induced SEU on hardening techniques and technology computer aided design device simulations.

I. Background

SOI technology is one example of a technology that competes with traditional bulk silicon. The key feature of SOI, which can be observed in Fig. 1, is an isolating BOX layer below the active silicon. This isolating layer prevents the traditional *n-p-n-p* structure associated with latchup in bulk silicon [4].

Beyond traditional reliability concerns such as leakage current, switching speed, and oxide integrity, the environment may contain additional concerns for proper device operation. It has long been observed that the interaction of radiation with semiconductor devices and materials can result in undesirable changes in device operating parameters [5], [6]. These are primary

concerns for missions that are exposed to harsh radiation environments, for example space, avionics, medical, and military applications. When considering the consequences of mission failure in the context of such important, and often expensive, objectives, ensuring the proper function of the microelectronics supporting these operations becomes a high priority.

SOI technology exhibits several inherent advantages when considering SEEs as compared to equivalent bulk technologies. As mentioned previously, the presence of the isolating BOX layer eliminates the possibility of device latchup, including SEL [4]. SOI presents a reduced volume for the generation and collection of eh pairs due to the thin layer of active silicon. Reduction in the sensitive volume of single transistors has also resulted in a reduction in the SEU cross section in comparison to bulk devices due to their larger sensitive volumes [7]. The presence of the BOX also eliminates the so called “field-funneling” effect, where the generation of dense columns of eh pairs near a depletion region perturbs the electric field and results in an increase in collected charge from the substrate region of the device.

II. Space Radiation Environment

The spacecraft orbit and shielding determines the radiation environment a device experiences during a mission. For example, the environment at geosynchronous earth orbit (GEO) experiences higher fluxes of heavy ions than that of low-earth orbit (LEO) [8]. In the LEO environment, magnetic fields around earth trap many energetic protons and electrons resulting in radiation belts. Magnetic field lines converge at points called the magnetic poles; these are regions where the particles flux is higher due to the sparseness of earth's magnetic field in those regions. The flux of heavier ions at LEO is diminished greatly due to the protection provided by the earth's magnetic field and atmosphere.

Much of the LEO environment consists of protons and helium ions, or alpha particles, as shown in Fig. 2. Solar activity results in the expulsion of protons and alpha particles. The origin of many of the particles in the GCR environment is from cataclysmic events such as nova and super nova where the energy released in the event is sufficient to fuse the heavier elements [8]. Random fluctuations in solar activity result in an ever-changing radiation environment for orbiting spacecraft.

Fig. 2. The GCR differential energy flux of particles at GEO, after [8]. Protons and helium ions dominate the GCR in this energy range. The peak-energy differential flux is a maximum for most particles between 100 MeV/u and 1 GeV/u.

It is well known that the interaction of these particles with semiconductor devices can have undesirable effects on device, circuit, and system level operation of microelectronics. These effects include threshold voltage shift, increased leakage current, error propagation and erroneous bit flips. Only the effects of heavy ions in modern SOI devices and the implications of secondary electron generation on normal device operation will be considered in this work.

III. Radiation Effects – Single Event Effects

Radiation affects microelectronic devices either by ionizing or nonionizing energy loss. While both of these physical interactions have important implications, the main focus of the work is ionizing radiation effects within semiconductor devices. Ionizing radiation events can further be divided into effects resulting from single particle events, which are known as SEEs, and cumulative effects resulting from the accumulation of charge in isolating oxide layers, which

are referred to as total ionizing dose (TID) effects. This study focuses on the consequences of heavy ion interactions with material.

Incident heavy ions experience coulomb interactions with valence band electrons and transfer energy to the semiconductor material [9]. Sufficient energy transfer results in the generation of electron-hole pairs (eh pairs). The generated, dense columns of eh pairs can be collected in and around depletion regions by the presence of an electric field, and may impact device operation. The presence of carriers in sensitive regions of microelectronic structures can result in a transient on the output terminal of a device; the induced transient can impact subsequent devices and circuits, such as changing the state of a latch or memory cell.

SEEs can be broken down destructive, or hard errors, and non-destructive effects, or soft errors. In this work we will focus on non-destructive SEEs. Non-destructive effects include single event transients (SETs) and SEU. SETs are the anomalous transient response of the output current or voltage signal in response to a single event. Single event upset (SEU) is the change of state of a memory element to some erroneous value due to a single event. These types of events are typically non-destructive in nature, and result in erroneous behavior of the impacted circuits. This study focuses on SEUs.

The vulnerability of a device or circuit element to SEU has been traditionally evaluated using linear energy transfer, or LET, as a metric for a single particle event to induce an upset event. LET is defined to be the rate of energy lost per unit path length in a given material, and can be expressed as,

$$LET = \frac{1}{\rho} \cdot \frac{dE_{ion}}{dx}, \quad (1)$$

where ρ is the material density, and dE_{ion}/dx is the rate of energy loss for the incident ion. For SEEs, the LET metric relates energy loss by an incident particle to energy deposition (or charge generation) within the sensitive volume of a semiconductor device; this charge contributes to the overall device response to a single particle event. LET, which is an approximation to the stopping power of a heavy ion, is inherently a description of average energy lost by the ion per unit path length. As pointed out by Xapsos in [10], energy lost by the incident heavy ion may differ from energy deposited in the sensitive volume.

The charge required to change the state of a memory cell is known as the critical charge, Q_{crit} . Traditionally, a simple relationship between LET and charge generation has been assumed, that all energy lost by an incident heavy ion results in charge generation within the volume being considered. Applying LET to SEE analysis requires that the average energy deposition of the event is sufficient to predict the event response. Fig. 3 illustrates the relationship between the energy lost by the incident particle and the energy deposited within a volume [10]. For very energetic ions, much of the energy lost may escape the volume of interest in the form of secondary electrons or other physical processes.

Fig. 3. Fraction of an ion's energy lost within the sensitive volume as a function of the volume's average chord length for various ion energies per amu, after [10].

The collection of generated carriers is fundamental for understanding of SEEs. In SOI, charge collection takes place at the source and drain terminals by the drift mechanism due to the presence of electric fields at the drain-body and source-body junctions. For the purpose of single particle event modeling, the concept of sensitive volumes is used to characterize the contribution of charge from ionizing particle events. A sensitive volume is any volume of material where energy deposition contributes to the generation of carriers that directly influence the result of a single particle event. Traditionally in SOI, the sensitive volume has been restricted to the active silicon region below the gate since charge collection is limited by the presence of the BOX.

While insulation beneath the active device layer eliminates the inter-device latchup structure, there exists a strong bipolar structure within SOI device geometry. Like silicon-on-sapphire (SOS) technologies, SOI exhibits a parasitic bipolar structure [11], [12]. An ion strike on an *n*MOSFET results in the generation and storage of holes within the body of the device,

effectively lowering the barrier between the source and body junction of the device, which forward biases the junction until recombination processes eliminate enough of the holes to allow bias conditions to restore device operation [12]. This process results in amplification of single-event induced charge collection.

The generation of secondary electrons, δ -rays, occurs when energy is transferred from an energetic ionizing particle to a valence band electron in a material. These δ -rays then interact with the lattice structure of the material and generate eh pairs or undergo scattering events. Scattering events cause the δ -ray to transfer a significant fraction of its energy to nuclei or valence band electrons. In 1988, Stapor *et al.* [1] described how differences in the radial distribution of δ -rays produced by two ions with identical LETs, but different energies, could result in different SEU responses, calling into question the application of LET as a metric for evaluating SEE response. In 1992, Xapsos [10] outlined a statistical model for the application of LET to microelectronics. This firmly established a metric for determining the validity of LET for technology nodes with well-established sensitive volume geometries. Dodd *et al.* [13] published measurements six years later showing the LET metric was sufficient to characterize CMOS technology nodes larger than 250 nm. The LET metric has proven robust for many newer technologies that have critical charges exceeding 10 fC, and it continues to serve as the basis for the majority of SEE analysis. Weller *et al.* were among the first to discuss the implications of using LET in small volumes where statistical variation becomes significant for accurate event predictions [14]. Weller showed that the localization of charge generation was significantly more important than the incident particle's LET in determining resulting SETs magnitude.

IV. SEU Sensitivity of Modern SOI SRAMs

Thin-film SOI SEU cross sections exhibit an angular dependence due to the large aspect ratios of transistors [15]. In some cases, the increase in average chord length is sufficient to allow direct ionization from lightly ionizing particles, such as protons and alpha particles, to cause SEU [3], [15], [16].

In recent years, additional physical mechanisms have been required to explain SEU cross sections where LET alone has been insufficient [2], [17], [18], [19], [20]. A single ion that deposits energy in a sensitive volume may produce spatial and temporal charge distributions dramatically different than those produced by the average event as predicted by LET alone [14]. This is true for events involving nuclear reactions and those that produce energetic, secondary electrons, or δ -rays. Delta-rays undergo multiple scattering events near their ends of range; these scattering events may potentially deposit a significant amount of energy in relatively small volumes. When one considers the device geometry of modern SOI transistors and circuits, low energy δ -rays may scatter within these volumes and produce undesirable SETs or possibly even SEUs. As a consequence, it is important to determine if single δ -ray events can cause single-event effects.

Fig. 4. Trends in reducing feature sizes have resulted in an overall reduction in the critical charge of single inverter cells [21].

For SOI technologies, as feature size has scaled, there has been a corresponding reduction in critical charge (see Fig. 4) [21]. When compared to equivalent bulk processes, SOI exhibits a reduced critical charge. The reduction in critical charge is due to the presence of the parasitic bipolar structure, which as discussed earlier, results in enhanced charge collection on the output terminal. Critical charge of the magnitude seen in Fig. 4 is the result of collecting several hundred to several thousand electrons, significantly less than what is seen in equivalent bulk technologies [16], [22]. Consequently, current and next generation SOI technology is becoming increasingly susceptible to lightly ionizing particle events.

Recently, IBM has released information about the upcoming 22 nm technology node, which features an SRAM with areal density of $0.1 \mu\text{m}^2$ [23]. The SRAM has dimensions of $0.18 \mu\text{m} \times 0.554 \mu\text{m}$ and is shown in Fig. 5.

Fig. 5. Top down SEM of the IBM 22 nm SOI CMOS SRAM cell with an areal density of $0.1 \mu\text{m}^2$ and dimensions of $0.18 \mu\text{m}$ and $0.554 \mu\text{m}$ [15].

In order to estimate the critical charge for the 22 nm technology node, we first estimate the gate capacitance according to

$$C_{ox} = \frac{\epsilon_r \epsilon_0 A}{x_{ox}}, \quad (2)$$

where ϵ_0 is permittivity, ϵ_r is the relative dielectric constant, A is the area of the gate and x_{ox} is the gate oxide thickness. By extracting the area of the gate from [23] and utilizing the effective oxide thickness obtained from the ITRS roadmap for 22 nm devices, one can estimate the gate capacitance for this technology node. Using the static noise margin, V_{SNM} , for the SRAM cell in [23], the critical charge for the technology node is approximated to be

$$Q_{crit} = C_{ox} V_{SNM}, \quad (3)$$

This estimation yields a critical charge of 0.08 fC required to upset a cell in this technology node. This amount of charge is equivalent to depositing 1.8 keV of energy, or 500 electrons, in the sensitive volume of the device.

The remainder of this paper is organized as follows. Chapter II will discuss the physics of δ -rays, including generation, energy loss mechanisms, and thermalization. Chapter III will discuss heavy ion track structure and how it relates to δ -ray events. Chapter IV describes the significance of δ -ray events for SRAMs in modern SOI technology nodes. Chapter V concludes.

CHAPTER II

DELTA-RAY PHYSICS

I. Introduction

Modeling of electron and positron interactions in materials is fundamental to understanding the radial track structure of ions for applications such as radiation therapy treatment, single-event effects, radiation detection, damage, and dosimetry. The origin of the term δ -ray comes from work performed by J. J. Thomson in relation to the liberation of electrons from their atoms by alpha particles [24]. In the 1960s, research performed by Kobetich and Katz focused on the development of a relationship for the transmission of δ -rays through planar sheets of matter [25], [26]. This enabled the formulation of a simple relationship for the energy dependence of δ -rays in a given medium that achieved good agreement with experimental data at the time [25],[26]. The development of a theory for the energy-range relationship was then applied to the problem of characterizing the dose-radius relationship, or energy deposition, as a function of radial distance from an ion track [26], [27]. In [25] and [26], Katz explores the effects of the ionization track structure for energetic heavy ions in various materials and how these events result in radiation-induced damage due to large energy deposition events immediately surrounding the ion track core.

In this section, we discuss generation of δ -rays by an incident heavy ion, the range of δ -rays in a material, the various scattering mechanisms δ -rays undergo in differing energy ranges, and energy loss mechanisms associated with energy deposition in semiconductor materials. This

information will then be presented in the form of a simulation framework for modeling the interaction of δ -rays with small volumes of material, in this case silicon, which is intended to represent the sensitive volume of a modern SOI SRAM.

II. Delta-Ray Generation

As heavy ions pass through material, they undergo Coulomb interactions with the electron gas, which is composed primarily of valence band electrons. The magnitude of this interaction depends on the velocity of the incident ion relative to the Fermi velocity, v_0 [9]. As the incident ion velocity approaches the Fermi velocity, interactions between the ion and the electron gas of the material increase the electronic stopping power, S_e , of the ion, which is the rate of energy lost per unit path length.

An incident particle's impact parameter, denoted b , is the normal distance between an incident particle and target, and effective charge of the ion govern the amount of energy an incident ion can impart in a two-particle interaction as seen in Fig. 6. In these types of collisions, many electrons may gain enough energy in these interactions to exceed the binding energy of the material and be free to move throughout the target medium. If the electron energy is such that the band structure of the material has little or no impact on its motion, then these free electrons are referred to as δ -rays. The result of the impact parameter is a distribution of initial energies for the generated δ -rays in any single ionizing event.

Utilizing Monte-Carlo Radiative Energy Deposition (MRED) [29] to simulate the generation of δ -rays by the incident particle within the material, initial energy of δ -rays generated within a target silicon block with dimensions of several millimeters on each side is tracked. MRED is a Monte-Carlo radiation transport code, which is based on the Geant4 [30] toolkit. A series of distributions of initial δ -ray energy from several incident particles with differing kinematical factors for Coulomb interactions can be seen in Fig. 7.

Fig. 7. Initial energy distribution for the generated δ -rays within a silicon block by several incident particles with different kinematics factors for Coulomb interactions.

The distributions shown in Fig. 7 illustrate the impact that kinematics and effective charge have on the generation of δ -rays in a given single-ionizing particle event. The number of δ -rays generated is a function of the effective charge of the incident ion, or the net charge the incident particle can exert on electrons in Coulomb interactions. The relative velocity of the incident particle in the medium and the kinematics of the ion determine the maximum energy that an electron can gain. A relativistic estimation of the maximum energy, E_e , that can be transferred to a δ -ray via Coulomb interaction with a heavy ion, a particle whose mass is significantly greater than that of an electron, is given by the kinematic equation:

$$E_e = 2m_e c^2 \gamma^2 \beta^2 \quad (4)$$

where $m_e c^2$ is the electron rest energy, β is the relative velocity, and γ is the Lorentz factor [31], [32]. For very energetic ions, it becomes necessary to account for relativistic interactions in the kinematics of these interactions. A classical calculation of Eq. (4) indicates a maximum observable energy of 1 MeV for δ -rays generated by 500 MeV/u Fe; however, the relativistic calculation, as in Eq. (4), and MRED simulations result in the generation of δ -rays with energies up to 1.4 MeV. It is important to understand the relationship between δ -ray energy and range; this will be explored in the next section.

III. Delta-Ray Range

Since the radial track structure of heavy ions is likely to become increasingly important for energy deposition events in sensitive, small volume devices, we must investigate the relationship between kinetic energy of an δ -ray and its range within the target material. In [25], Kobetich described the range of an incident δ -ray in Aluminum according to,

$$R = AE \left(1 - \frac{B}{1 + CE} \right), \quad (5)$$

where E is the δ -ray energy in the range of 300 eV to 3 MeV, A is $5.37 \times 10^{-4} \text{ g}\cdot\text{cm}^{-2}$, B is 0.9815, and C is $3.123 \times 10^{-3} \text{ keV}^{-1}$. Plots of this range estimation as a function of δ -ray energy are shown in Fig. 8 along with experimental values from [25].

Fig. 8. Estimation of the range from Eq (5), in units of g cm⁻², of electrons as a function of energy [25]. The estimation, solid line, is shown to have strong agreement with experimental data over a wide range of energy.

The range estimation of Eq. (5) provides excellent agreement to experimental data over a wide energy range as shown in Fig. 8. While it provides an excellent expectation of the average penetration depth of δ -rays in a material, charged particle interactions within material is inherently a statistical process. Therefore, it is necessary to consider the statistical nature of the problem from the standpoint of variation in range and the average distance between energy loss events for the δ -ray.

Akkerman *et al.* from energy-loss function theory based on the complex dielectric function in [33] and [34], which relies on mean field approximations of the target material [33], we gain knowledge of the average distance between inelastic scattering events for δ -rays, the inelastic mean free path (IMFP) in a given medium. Knowledge of the average distance between energy loss events and stopping power for an incident δ -ray allow for an approximation of the range of δ -rays in materials is known as the continuous slowing down approximation (CSDA), and is based around the earlier experimental work and theory on δ -rays previously discussed. Akkerman *et al.* describes the IMFP in [33]; the results of their modeling are shown in Fig. 9 below.

Fig. 9. The mean free path (MFP), or average distance traversed between scattering events, for protons and electrons as a function of energy, after [33].

Fig. 9 shows that the IMFP has strong energy dependence. At low energies, below several hundred eV, there is large variability in the IMFP, which makes determining average distance between scattering events difficult [33], [35]. Low energy δ -rays, less than a few hundred eV, is on the order of a few nanometers, and for the purposes of this work, it is assumed that the energy is deposited locally in the next scattering event as the δ -ray thermalizes back into the band structure of the lattice.

Fig. 10. CSDA range approximation for electrons in silicon from [34].

Fig. 10 shows an approximation of the range of an electron with a given energy in silicon using approximations based on stopping power and the IMFP [36]. The stopping power of δ -rays in materials can be used to estimate the average electron range in terms of a continuous energy loss to the surrounding material, which is known as the CSDA range [33], [35]. Like the IMFP from [33], the CSDA range has strong energy dependence. Due to the variability in IMFP below 10 keV, it is difficult to define a statistically meaningful average range. The lateral range of a given electron can be estimated from an electron's CSDA range as well as the initial angle of its trajectory relative to the ion track. When δ -rays lose sufficient energy, the IMFP, which is a strong function of the δ -ray energy as discussed earlier, decreases until the electron thermalizes back into the material band structure.

For the purposes of δ -ray transport in materials using MRED [29] coupled with Penelope 2008 [35], the energy where electrons thermalize and deposit the remainder of their energy locally occurs below 50 eV [35]. Penelope 2008 is a Monte-Carlo transport code dealing explicitly with the complexities of photons, positrons and electrons in materials [35]. Analyzing the motion of δ -rays, with initial energies shown in Fig. 7, within a large silicon block illustrates the distribution of lateral ranges, the distance between the ion track core and the stopping point for a δ -ray, for a single ionizing particle event in Fig. 11.

Fig. 11. Lateral range distribution of δ -rays in a silicon block generated by several incident particles with different kinematics factors for Coulomb interactions.

Many of the generated δ -rays have ranges of hundreds of micrometers; the maximum range is strongly coupled to the maximum δ -ray energy. This indicates there exists a maximum lateral range where a δ -ray can impact the normal operation of a nearby microelectronic structure. The

probability that a δ -ray will interact with the sensitive volume of a microelectronic device is related to the number of δ -rays capable of traversing the lateral distance between the incident ion track and the sensitive volume; this will be explored in depth in Chapter 4. We will rely on the insight provided in this section when we consider the radial track structure of a single event particle strike in Chapter 3.

IV. Delta-Ray Scattering Events

Once an electron gains enough energy, and is liberated from the band structure of the material, it begins to interact with the electron gas of the crystal structure through elastic and inelastic scattering events with electrons in the valance and conduction bands. A graphical representation of these types of scattering events can be seen in Fig. 12.

Fig. 12. Illustration of (a) elastic and (b) inelastic scattering events with incident electrons having energy, E , and undergoing energy loss, W [35].

Elastic scattering is defined in [35] as scattering events that result in a final quantum state that is the same as the initial state prior to the electron scattering event. Nominally, this state is the ground state for the system. Therefore, no tertiary particles or eh pairs are created in these

scattering events. The energy range of electrons involved in these scattering events is typically larger than a few hundred eV [35].

Inelastic scattering is defined to be collisions in which the target atom is left in an excited state [35]. The de-excitation of the atom results in either the emission of an x-ray or Auger electron in order to return to a neutral state. That is, the incident electron undergoes energy loss, W , while producing a secondary electron in the collision which has energy, $W - U_i$, where U_i is the energy associated with a vacancy in the i th shell of the target atomic system. Inelastic scattering events result primarily from collisions involving electrons with energies from several keV to several hundred keV [35]. Additionally, they may result in the creation of tertiary particles; that is, enough energy is transferred to the target electron that it becomes a free particle or δ -ray.

V. Delta-Ray Energy Loss

Once freed from interaction with the band structure of the material, δ -rays begin to interact with the electron gas of the crystal structure through elastic and inelastic scattering events with valence and conduction band electrons. Elastic scattering events do not directly result in energy deposition capable of generating sufficient carriers in the sensitive volume of a device in order to result in circuit level transient effects. Inelastic scattering dominates δ -ray interactions below energies of 100 keV [35]. For SEEs, the primary δ -ray energy deposition mechanism is inelastic scattering events. Inelastic scattering events between δ -rays and valence band electrons involve similar masses and, as a consequence, these events can transfer large amounts of the incident δ -ray's energy to the tertiary δ -ray, approximately $W/2$ with a scattering angle of $\pi/2$ [35]. The sequence of scattering events with an energetic δ -ray and tertiary δ -rays can result in large energy deposition events in relatively small volumes. Fig. 13 shows the results of a simulation of

a 10 keV δ -ray incident on a 50 nm cube of silicon, which is representative of realistic sensitive volumes in modern SOI technologies.

Fig. 13. Illustration of 10 keV scattering events in a 50 nm cube of silicon. Event (a) shows a 2.1 keV energy deposition event that produces additional δ -rays in a chain of inelastic scattering events. Event (b) shows a 2.6 keV energy deposition event that produces several tertiary δ -rays in a series of inelastic scattering events.

The chain of inelastic scattering events depicted in Fig. 13a produced an energy deposition of 2.1 keV. This event is a single inelastic scattering event that resulted in a cascade of scattering events involving the tertiary δ -rays. Similarly, Fig. 13b illustrates a 2.6 keV energy deposition event in a series of inelastic scattering events. This event resulted in the generation of multiple tertiary δ -rays along the track of the incident δ -ray (which was approximately 50 nm in length), all of which stop within the 50 nm silicon cube. While the incident δ -ray does not stop within the 50 nm silicon cube in either of the events depicted in Fig. 13, energy is transferred to δ -rays and

the total energy deposited in these volumes exceeds the estimation of critical energy required to produce a SEU in the 22 nm SOI technology of [23].

CHAPTER III

IONIZATION TRACK STRUCTURE

I. Background

Understanding of the ionization track structure of charged particles in materials has been of importance since the early 1950s. Early work by Kobetich [25] and Katz [26] sought to understand the ionization track structure through modeling the range of δ -rays within the medium. Their work has since been extended to fields such as radiation detection, radiation damage in dielectrics, and radiation therapies for biological treatments.

The δ -ray range model of Kobetich and Katz was applied to the problem of ionization track structure. The dose versus radius of these models is shown in Fig. 14 for events in water at several relative velocities. For a given particle, the radial extension of the ionization track structure depends on the relative velocity. For small values of relative velocity, Fig. 14 shows that the radial dose deposited is larger near the core of the ion track. As energy of the incident particle decreases, there is some range where the track structure of more energetic particles begins to deposit more energy, and consequently a larger dose. These concepts will be explored further later in this chapter.

For very energetic particles, radial dose is a decreasing function of the particle's energy. The kinematics of Coulomb interactions is important for radial track structure of single events

involving charged particles (see Chapter II). As an extension of that result, the implications of radial track structure describe the ionization track.

Fig. 14. Spatial distribution of ionization energy in water for incident particles with differing relative velocity, from [26]. These calculations based on Katz theory describe the average dose deposited as a function of radial distance, t , from the incident ion track.

II. Linear Energy Transfer as a Metric for SEU

Stopping power, S , is defined as the rate of energy lost by an incident particle per unit path length in a medium. This parameter is often approximated by the linear energy transfer, LET , of a particle in a given medium. A typical stopping power versus penetration depth curve, or Bragg curve, is shown in Fig. 15.

Fig. 15. The electronic stopping power, S_e , as a function of incident ion energy is shown for Cu in Si. The horizontal line indicates that two distinctive energies, 25 MeV and 410 MeV Cu are capable of generating the same amount of charge for a given path length. However, these two energies produce vastly different charge generation profiles. After [1].

We can see from the Bragg curve in Fig. 15 that for a particle and small range of LET values, there exist multiple energies that have the same stopping power. However, from knowledge of δ -ray ranges in Chapter II, the resulting kinematics of the Coulomb interactions in these single events will result in different radial track structures.

In 1988, Stapor *et al.* described how two particles with similar LETs would have vastly differing track structures, and therefore the possibility for differing SEU responses [1]. This was the first time that the use of LET as a metric for SEU had been questioned. In 1992, Xapsos outlined a statistical model for the application of LET to microelectronics for the purpose of

continuing the use of this metric in modeling SEEs. In doing so, Xapsos defines the relationship between energy loss by an incident particle and the radially deposited dose that results in carrier generation within the sensitive volume of a microelectronic device. In 1998, Dodd *et al.* showed that LET as a metric for modeling SEU was still viable since device geometry and critical charge were not sufficiently small to be impacted by the ionization track structure of the incident particles considered [13]. For modern SOI devices with critical charges on the order of those found in [16],[3],[37], the role of ionization track structure must once again be reconsidered.

Weller *et al.*, described differences in the simulated response of submicron MOSFET devices between averaged events based on LET and randomly generated, physically realistic single event strikes. While a wide variety of device responses were observed for single event profiles, Weller identifies those involving δ -rays to produce large transient responses in comparison to those based on average LET [14]. These δ -ray induced transient events, due to the localization of energy deposition, are of a similar order of magnitude as nuclear reaction events [14]. However, δ -ray generation is far more common than nuclear reactions, indicating a greater need for understanding these interactions and their impact on device response.

III. Ionization Track Structure

In Fig. 16, e - h pair density as a function of radial distance from the ion track at a depth of 1 μm in silicon illustrates the difference in ionization track structure for two ions with similar LETs but differing energies [1]. The variation in ionization track structure is coupled to the kinematics of Coulomb interactions between the incident particle and a quasi-stationary electron in the valance band. Consequently, higher maximum kinematic factor results in a larger ionization track radius.

Fig. 16. Calculated electron-hole pair density generation is shown as a function of radial distance from the ion-track at a depth of 1 μm within a volume of silicon for (a) 395 MeV Cu and (b) 25 MeV Cu, after [1].

While the stopping power of each copper ion is the same, that is on average they lose the same amount of energy per unit path length in a material, their ionization track structure differs, with the less energetic particle having a very dense track structure around the core of the ion track, and the more energetic ion has a larger lateral extension from core of the ion track. As the incident particle loses energy, the kinematics begin to relax and, as a result, we see a narrowing of the ionization track radius with greater penetration depth into the material, as seen in Fig. 16. This process of energy loss and narrowing of the ionization track radius continues until the

particle comes to a complete stop at which point the track structure has collapsed on the incident particle completely.

Fig. 17. Electron-hole pair generation is shown as a function of radial distance from the ion-track and depth within a volume of silicon for 250 MeV Fe, after [1]. Results indicate that while the ion track radius is initially on the order of a micrometer, it quickly collapses in on itself as the incident particle loses energy. These results are consistent with results from Chapter II, which indicate the kinematics of the Coulomb interaction determine the ion track radius.

The ion track radii seen in Fig. 17 are large when considering modern device density [23]. When evaluating the single event response for a given heavy ion, more energetic ions involve greater uncertainty, since effects from a wider track structure are not captured in modern sensitive volume models that rely explicitly on LET as a metric for SEU. When considering single-event upsets in extremely sensitive devices, it is necessary to have a thorough understanding of ionization track structure in order to understand the vulnerability of these types of devices. Due to the variability of ion track structure, it is also important to consider the incident particles penetration depth, straggle, and angle when evaluating the single event response of sensitive technology nodes. In the following sections, we will illustrate the ionization

track structure for particles with similar mass, but varying energy, and show the single event upset response due to each is likely to be different for sensitive modern technologies.

Howard *et al.* discussed an experimental approach to resolving differences in track structure by using a series of concentric, cylindrical Schottky barriers to collect charge as a function of radial distance from the ion strike location [38]. By striking the center of the cylindrical structure, Howard demonstrated by numerical simulations that differences in track structure resulted in distinct charge collection profiles as a function of radial distance. Howard showed this for different ions with similar LET and a single ion with different incident energy but similar LET [38].

IV. Monte Carlo Simulation of Ionization Track Structure

The radial extension of the particle track is a strong function of the kinematics between the incident particle and the electron; see the discussion of Eq. (4). As a result, the particle track radius is widest when the particle first enters the material, and then it slowly collapses as the particle loses energy. If plotted as a function of depth as in [1], the radial track structure takes on a conical shape. In order to evaluate the extent that δ -rays may impact high-density memories, we must consider the radial extension of these long-range, high-energy δ -ray events due to radial track structure. In [27], Zhang describes the dose deposited as a function of radial distance t ,

$$D(t) = \frac{Ne^4Z^{*2}}{\alpha m_e c^2 \beta^2 t} \cdot \frac{\left(1 - \frac{t+\theta}{T+\theta}\right)^{1/\alpha}}{t + \theta}, \quad (6)$$

where N is the electron density, e is elementary charge, m_e is the electron mass, Z^* is the effective charge of the incident particle, c is the speed of light in vacuum, β is the relative velocity in the medium, T is the range of δ -rays with energy W , where W is the relativistic maximum δ -ray

energy, θ is the range of δ -rays with kinetic energy equal to the ionization potential I , and α is a fitting parameter as defined in [27], [39], and [40].

Kobayashi previously utilized MRED to investigate the ionization track structure of protons and alpha particles in [40], and found the simulation results in good agreement with the well-established Katz theory. In this work, Kobayashi uses a multi-layer concentric cylindrical target, similar in concept to the concentric Schottky barrier ring of Howard [38], to characterize energy deposition as a function of radial distance from the core of an ion track by δ -rays at a fixed depth within the material. A graphical illustration of the multi-layer concentric cylindrical target can be seen below in Fig. 18.

Fig. 18. Graphical illustration of the multi-layer concentric cylindrical target (MCC), after [40]. Incident particles traverse the innermost cylinder of the target, while contributions to energy deposition events are measured in the outer cylindrical volumes with varying radial thicknesses. Material is placed on the front and rear of the main 1 μm set of cylinders to maintain charged particle equilibrium within the structure of interest.

This structure has a series of concentric cylinders with varying inner and outer radii. MRED sensitive detectors are attached to each cylinder to allow tracking of energy deposition events involving δ -rays. Material is placed both in front and behind the target set of cylinders to provide charged particle equilibrium for the detector environment. A beam of particles is incident on the core cylinder of the target. Since in this work we are concerned with track structure effects primarily in the sensitive volume region of SOI devices, the target structure is comprised entirely of silicon. The track structure results of [40] are shown below.

Fig. 19. Shows the deposited dose as a function of radial distance as predicted by Katz theory and MRED simulation of 100 MeV protons on a multi-concentric cylindrical target, after [40]. Results indicate that MRED is capable of accurately predicting the radial track structure of heavy ions in materials according to well-established theory of ionization track structure.

The results of Fig. 19 show good agreement with Katz theory for distances greater than 10 nm surrounding the ion track. Small deviation from Katz theory at radial distances less than 10 nm is

likely due to intentional variation in the beam dither intrinsic to MRED [41] or lateral straggle of the incident particles within the target.

The MCC structure of [40], as seen in Fig. 18, was enlarged in this work to allow investigation of radially deposited dose with heavier, energetic particles. Extending the work of [40] allows the proof of concept for the discussion of Chapters II and III with Penelope 2008 enabled in MRED, and the detailed study of how δ -rays deposit energy in volumes representative of sub-65 nm SOI memory cells. The maximum radial extension of the ion track considered here was 100 μm , with 20 μm of silicon beyond that to maintain charged particle equilibrium in the radial direction from the ion track. The overall thickness of the detector layer was 5 μm , buffer layers 35 μm were placed in front of and behind the MCC detector target to maintain charged particle equilibrium.

Fig. 20. Ionization track structure of 280 MeV Fe and 28 GeV Fe within the large silicon MCC structure. Results indicate that for small radii around the core of the ion track, δ -rays generated by 280 MeV Fe deposit more energy, and result larger energy deposition events than 28 GeV Fe. However, at several hundred micrometers from the ion track, δ -rays generated by 28 GeV deposit more energy, and result in very large energy deposition events at several tens to hundreds of micrometers.

Fig. 20 shows a box plot of dose versus radial distance from the incident particle track for 28 GeV and 280 MeV Fe. The upper and lower box represents one tenth of the maximum likely dose event for the observed energy deposition spectrum. The upper whisker represents the maximum energy deposition event at a given radius. This type of plot provides statistical insight into the radial distance from an incident ion where the most likely and extreme dose exceed the dose required to upset a given technology node.

Fig. 20 shows a dramatic difference in the deposited dose for equivalent radial distances for the highly ionizing 280 MeV Fe and less ionizing 28 GeV Fe. 280 MeV Fe deposits a larger dose than 28 GeV Fe in the volumes near the ion track, while further from the ion track structure (> 800 nm), 28 GeV Fe deposits significantly more dose due to the longer range of δ -rays generated in these events. Several hundred nanometers from the ion track, many of the δ -rays generated by the 280 MeV particles are near their ends of range while δ -rays generated by the 28 GeV particles continue on and interact with the outer cylindrical shells of the target.

Additionally, variation in energy deposition from δ -ray events varies the deposited dose by several orders of magnitude, even at large radial distances. This further establishes that the area most impacted by 280 MeV Fe strikes is immediately around the ion track and indicates that using LET as a metric for modeling effects from this ion is justified. However, for 28 GeV Fe ions, the issue is complicated due to the large radial extension of the ion track. The use of LET as a metric for modeling these types of high-energy events is not representative of the physical phenomena contributing to SEUs in devices with very small critical charges.

Using the estimated dose of $14.4 \text{ MeV}/\mu\text{m}^3$ required to cause an upset in the 22 nm technology, we can see that the maximum distance where upsets will occur for 280 MeV Fe is around a micrometer from the incident particle track, and the extreme distance, that associated with the upper whisker, is around two micrometers. When the same consideration is made with regard to 28 GeV Fe, we notice an increase in the maximum average distance to observe an upset event (around a 1.5 micrometers); however, the extreme distance where the dose deposited exceeds the dose required to cause an upset is greater than 30 micrometers.

CHAPTER IV

ENERGY DEPOSITION IN HIGHLY SCALED SOI SRAMS

I. Simulation Approach

MRED [29] and Penelope 2008 [35] were used to study the impact of δ -rays on the SEU response of highly scaled SOI SRAMs. A top-down view of the structure used for the simulation can be seen in Fig. 21. The black coloring represents the nearest neighbor SRAM cell at a distance of $0.18\text{ }\mu\text{m}$, red coloring represents an SRAM at a distance of $0.554\text{ }\mu\text{m}$, and blue represents an SRAM at a distance of $1.17\text{ }\mu\text{m}$. The green cubes represent the sensitive volumes of individual SRAM cells. The structure has an area of $3\text{ mm} \times 3\text{ mm}$ and a thickness of $500\text{ }\mu\text{m}$. Sensitive volumes representing SRAMs were placed at intervals of $0.18\text{ }\mu\text{m}$ along the x-axis and $0.554\text{ }\mu\text{m}$ along the y-axis from the irradiated cell. The back end of line (BEOL) material consists of SiO_2 , copper, and a layer of tungsten representing a via between metallization layers; the total BEOL thickness is approximately $3\text{ }\mu\text{m}$ and represents a six-level-metal process. The BEOL has alternating layers of high-density and low-density material, and produces charged particle equilibrium for single events.

Fig. 21. Mock up of simulated SRAM array structure. Dimensions are representative of a 22 nm SRAM with 0.18 μm vertically and 0.554 μm horizontally. Black coloring represents an SRAM cell 0.18 μm from the irradiated SRAM cell, red represents an SRAM cell 0.554 μm from the irradiated cell, and blue represents an SRAM cell 1.17 μm from the irradiated SRAM cell.

The beam was randomized over the area of the target cell and energy deposition was recorded in the surrounding array of SRAM sensitive volumes. The result of each simulation is a histogram representing the spectrum of simulated energy deposition events for each volume. The sensitive volumes were modeled as 50 nm cubes, which are consistent with the sensitive volume geometries of advanced SRAMs [16], [3], [23]. Filters were implemented that enable a lower bound for tracking of δ -rays with track lengths longer than 180 nm, which reduces the computational complexity of simulations while maintaining relevance to the geometry of a modern SRAM array.

Charge collection mechanisms in isolated devices occur on a time scale much longer than energy deposition events in the simulated device structure, so the transient response of the device is not modeled explicitly [40]. Instead, energy deposition within a single volume is used to indicate the occurrence of an upset event. Any event that results in energy deposition greater than

1.8 keV within a single sensitive volume, the estimated critical energy for the 22 nm technology in [23], is considered to be an upset event. Thus, the probability of the occurrence of an upset event is the cumulative probability of depositing a given energy or greater within the sensitive volume of a device. We compute the probability of δ -rays depositing a given amount of energy or greater in a sensitive volume using the following formula:

$$P(E_i) = \frac{\int_{j \geq i}^{\infty} N(E_j)}{\int_{j=0}^{\infty} N(E_j)}, \quad (7)$$

where $N(E_i)$ is the number of events depositing a given energy, E_i . In order to isolate the specific mechanisms and ranges of energy deposition resulting from δ -rays, contributions to deposited energy resulting from nuclear reactions are not included in the simulation results.

Several ions were considered, including 100 MeV protons, 1 GeV protons, 280 MeV Fe and 28 GeV Fe. Events were simulated at normal and 60° angles of incidence. Contributions to energy deposition from both single and multiple δ -ray events are considered in these simulations.

II. Simulation Results for Lightly Ionizing Particles

Fig. 22 shows the cumulative probability distribution of energy deposition in the simulated structure from 100 MeV protons at normal incidence. The colors of the lines used to plot the probabilities indicate the spatial location of the sensitive volumes relative to the target cell, as defined in Fig. 21.

Fig. 22. Cumulative probability distribution for normally incident 100 MeV protons. The color scheme of the plot follows Fig. 21. The distance between SRAM cells and the target SRAM is denoted by a distance, r . Values on the x-axis represent energy deposited by δ -rays in nearby volumes.

100 MeV protons are very lightly ionizing due to their low effective- Z , with an LET of $5.86 \times 10^{-3} \text{ MeV} \cdot \text{cm}^2/\text{mg}$. The δ -rays generated by 100 MeV protons have a maximum energy of 250 keV. Direct ionization from the proton itself is localized around its track, while the δ -rays produced are capable of traveling many micrometers. The majority of events result in energy deposition of several hundred eV or less, as seen in Fig. 22. However, we observe scattering events occurring within the sensitive geometry of neighboring and nonadjacent devices that exceed the estimated critical energy threshold calculated from [23]. These results indicate that δ -rays generated by energetic, lightly ionizing particles, such as 100 MeV protons, are capable of depositing energy sufficient to generate 0.13 fC at a distance of 0.18 μm and 0.1 fC at a distance of 1.17 μm from the target SRAM cell.

Fig. 23. Cumulative probability distribution for normally incident 1 GeV protons. The color scheme of the plot follows Fig. 21. The distance between SRAM cells and the target SRAM is denoted by a distance, r . Values on the x-axis represent energy deposited by δ -rays in nearby volumes.

Fig. 23 shows a comparison of the cumulative probability distributions for energy deposited in the simulated device structure due to 1 GeV and 100 MeV protons at normal incidence. The LET of 1 GeV protons is $1.81 \times 10^{-3} \text{ MeV} \cdot \text{cm}^2/\text{mg}$ in silicon; with such a low rate of ionization by the primary particle, the rate of δ -ray generation is reduced significantly compared to 100 MeV protons. As the rate of δ -ray generation decreases, the relative probability of depositing low amounts of energy, less than the critical energy threshold, decreases. However, the δ -rays generated by 1 GeV protons are, on average, much more energetic than those produced by 100 MeV protons. As a result of the higher average δ -ray energy, events produced by 1 GeV protons are capable of depositing more energy in small sensitive volumes than those produced by

100 MeV protons. In Fig. 23, this is seen more clearly in the sensitive volume located 1.17 μm from the strike location, where the tail of the curve extends due to contributions from higher energy events involving 1 GeV protons. Since the IMFP scales with increasing energy [33],[34],[35] in these simulated events, many of the generated δ -rays have significantly longer range than the structure considered thus far. These longer-range events may impact devices at great distances, potentially hundreds of micrometers, from the location of the incident particle strike as indicated by Fig. 11.

Since protons have a low LET, they do not produce a large concentration of δ -rays in a given single-particle event. This is consistent with the relatively low probabilities of single events with δ -ray energy deposition in excess of the energy threshold for the device geometry under consideration in Fig. 22 and Fig. 23. As discussed previously in Chapter 2, inelastic scattering events dominate energy loss mechanisms in the range of δ -ray energies produced by these two particles [35]. Consequently, the majority of energy deposition events in the sensitive volumes of the nearby devices are produced by inelastic scattering processes for δ -rays below 100 keV, including those above the estimated critical energy threshold. These results indicate that very lightly ionizing particles, such as energetic protons, are capable of generating δ -rays that can disrupt the normal operation of adjacent and nonadjacent devices. More importantly, when considering the CSDA range of higher energy δ -rays, we conclude that they are unlikely to stop within the sensitive volume of nearby devices on the scale considered here, but are capable of interacting with devices at even greater distances.

III. Simulation Results for Highly Ionizing Particles

Fig. 24 shows the interaction of 280 MeV Fe with the simulated device structure from Fig. 21. The solid white cylinder represents the inner core of the incident ion track of 280 MeV Fe.

Each red cylindrical tube represents the track of a δ -ray interacting with the material structure as it undergoes energy loss to the lattice and its electrons. The minimum energy tracked for the generation of δ -rays was 250 eV, while the minimum energy for δ -ray interactions was 50 eV.

Fig. 24. Simulation of 280 MeV Fe interacting with the simulated SRAM array structure. The solid white tube represents the incident ion track. Red tubes represent generated δ -rays along the ion track. The green structures represent the sensitive volumes of neighboring devices. The green bar, top right corner, represents a 5 μm distance.

As previously discussed, the range of electrons of these energies is on the order of a few nanometers. It is likely that if these low energy particles enter the sensitive region of a device, they will lose all of their energy within the sensitive volume. In Fig. 24, scattering events are clearly visible in many of the δ -ray tracks. The δ -ray tracks terminate when the energy is below the tracking threshold of 50 eV. The green cubes represent a sample of those used to monitor energy deposition in neighboring device structures.

Fig. 25. Simulation of 28 GeV Fe interacting with the simulated SRAM array structure. The solid white tube represents the incident ion track. Red tubes represent generated δ -rays along the ion track. The green structures represent the sensitive volumes of neighboring devices. The green bar, top right corner, represents a 5 μm distance.

Similarly, Fig. 25 shows the interaction of 28 GeV Fe with the simulated device structure representing a 22 nm SRAM. The differences between high LET 280 MeV Fe and low LET 28 GeV Fe radial track structures are very clear; fewer δ -rays are generated by single events involving 28 GeV Fe than 280 MeV Fe. Additionally, Fig. 24 and Fig. 25 show that the variation

in track lengths for δ -rays generated by 28 GeV Fe is much greater than that for 280 MeV Fe. This agrees with the results in Fig. 20, where the ranges of δ -rays from 280 MeV Fe are dramatically less than those of 28 GeV Fe. The increase in high-energy events due to these energetic δ -rays makes the application of LET to single events particularly difficult because of the variation in track structure relative to device spacing and sensitive volume geometry. While 280 MeV Fe is highly ionizing compared with the protons considered in the previous section ($\text{LET} = 21.7 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ in silicon), due to kinematics, the maximum energy δ -ray produced is 10 keV. The CSDA range of a 10 keV electron is $1.49 \text{ }\mu\text{m}$ in silicon [33],[34],[35], which means that there is a limitation to the radial extent of the ion track consistent with Fig. 20. As a result, δ -rays produced by the ion are restricted in the amount of influence they can exert upon neighboring devices. Therefore, the ion LET represents the effects of the deposited charge on the circuit response with acceptable accuracy. However, for low critical charge, small volume geometry circuits, δ -rays will be an important factor to consider when analyzing the SEU response.

Fig. 26. Cumulative probability distribution for normally incident 280 MeV Fe on simulated 22 nm SRAM array. The color scheme of the plot follows Fig. 21. The distance between SRAM cells and the target SRAM is denoted by a distance, r . Energy deposition represents energy deposited by δ -rays in neighboring volumes. The longer tails represent multiple δ -rays interacting within the sensitive volume of neighboring devices.

Fig. 26 plots the cumulative probability distribution for energy deposition in the three volumes indicated in Fig. 21 when the target area is irradiated with 280 MeV Fe ions. The probability of events in each volume decreases with increasing distance from the irradiated cell due to the constant energy loss electrons undergo as they traverse the structure and the cross section for producing high-energy, long-range δ -rays. This is shown by the difference in probability at the SEU threshold for devices located $0.18 \mu\text{m}$ and $1.17 \mu\text{m}$ from the strike location. There is a continuum of energy deposition from approximately 300 eV to 7 keV for the volume nearest to the irradiated SRAM cell, indicating that significant energy deposition events

occur in a very short spatial region around the ion track, which is consistent with the radially deposited dose relationship of Fig. 20. Events in greater than 10 keV in energy, associated with the long tails at 0.18 μm and 0.554 μm , are the result of multiple δ -rays scattering within the volume. These events result in more energy deposition than any single δ -ray could deposit. Events depositing up to 13.3 fC of charge were observed in the cell 0.18 μm from the irradiated cell, 4 fC in the cell at a distance of 0.554 μm , and 0.1 fC for the farthest cell, which is 1.17 μm from the irradiated cell.

Charge generation from δ -rays of these magnitudes is sufficient to produce circuit-level effects in current 45 and 65 nm device generations [16], [3]. Differences in experimental SEU data collected from a 65 nm SOI SRAM [16] for alpha particles and protons that have identical LETs may be explained by differences in the track structure between the two ions. This type of ion track structure effect is similar to that proposed by Stapor in [1]. Comparing the probability distributions in Figs. 22, 23 and 26, one concludes that there are dramatic implications on testing and SEU analysis methods for low critical charge circuits. The sensitivity of modern devices requires an awareness of the contribution to SEU probability and cross section from not only the incident particle, but also contributions from additional physical mechanisms, such as nuclear reactions and δ -rays. As a consequence, ground-based heavy ion experiments intended to provide insight into SEU upset cross sections must consider all of these factors during pre-test planning and post-test data analysis in order to model and estimate the SEU cross section accurately.

IV. Radial Track Structure and Angle of Incidence

The SRAM simulations described above show probability distributions for incident particles, but only consider the effects of δ -rays in a very small region around the irradiated SRAM cell. The original device structure was expanded, with additional sensitive volumes at larger radial

distances from the target SRAM cell, to study the radial extension of the ion track and the role it plays in δ -ray events. The probability distribution for 28 GeV Fe normally incident on the expanded device structure is shown in Fig. 27. We denote the distance between SRAM cells by a distance, r .

Fig. 27. 28 GeV Fe normally incident on the target cell. Energy deposition in devices significant distances from the struck cell are capable of exceeding the estimated critical energy threshold for 22 nm technology nodes. The distance between SRAM cells and the target SRAM is denoted by a distance, r .

Fig. 27 exhibits many of the features of Fig. 26. However, there are higher energy events due to a combination of single, large energy, and multiple δ -ray events. Also, energy deposition events were observed at significantly larger radial distances from the irradiated SRAM cell. Several events in excess of the upset threshold energy were observed on the order of 18 to 20 micrometers from the strike location, which is a factor of ten larger than that observed for

280 MeV Fe. Several smaller events, on the order of 300 eV, were observed at radial distances of 55 micrometers. While these events were not sufficient to produce circuit-level effects for technologies with the critical charge estimated here, future scaling of devices may shift critical charge into this range.

Fig. 28. 28 GeV Fe at 60° angle of incidence. The distance between SRAM cells and the target SRAM is denoted by a distance, r . The radial extension of the ion track into neighboring devices becomes worse as the angle of incidence increases. This results in increased energy deposition events at large distances from the target SRAM cell.

Thus far we have only considered normally incident particles. However, half of the isotropic galactic cosmic ray environment is incident at angles greater than 60° [42]. If we consider the type of track structures shown in Fig. 20, it becomes obvious that δ -ray events have a very strong dependence on the parent particle's angle of incidence. Fig. 28 shows the probability distribution

for 28 GeV Fe incident at 60° through the sensitive volume of the target SRAM cell. As the angle of incidence increases, the distance between the ion track and the sensitive volume of neighboring SRAM cells decreases, resulting in larger energy deposition for devices located at intermediate ranges between 5 to 10 micrometers. This is indicated by the relative shift to higher probabilities at the critical energy threshold for devices at these intermediate distances. There is an increase in events at larger radial distances (on the order of 55 to 58 μm) than those shown in Fig. 27, which had only a few counts. Again, these events are below the critical charge estimate of the 22 nm SRAM considered here, but these types of energy deposition events may impact future technologies, which are likely to be more sensitive as critical charge continues to decrease.

CHAPTER V

CONCLUSION

The impact of δ -rays on the SEU response of highly scaled technologies, including a 22 nm SOI SRAM, is analyzed. Monte-Carlo simulations were used to investigate interactions between the track structure of energetic heavy ions and an array of SRAMs representative of modern SOI technology nodes. Predictions indicate that single electrons can deposit enough energy in the sensitive volume of SRAM cells to cause upset. Simulation results indicate energy deposition from energetic δ -rays generated by lightly ionizing incident particles, such as 100 MeV protons, is sufficiently large to upset circuit nodes with critical charges less than 0.08 fC.

The probability for δ -rays to deposit energy at large radial distances from the incident particle strike location exhibits a dependence on the incident particle energy. For example, 280 MeV Fe results in a large probability to exceed an estimated upset threshold for energy deposition in a 22 nm SRAM 0.18 μm from the ion strike location. The same ion has no effect on SRAM cells with radial distances greater than 1.2 μm . Furthermore for very energetic ions, such as 28 GeV Fe, energy deposition in cells far removed from the ion strike location, potentially tens of micrometers, can be upset. Additionally, a strong angular dependence is observed for these very energetic particles that result in an increased probability to exceed the estimated upset threshold at distances greater than 5 μm from the ion strike location.

Consequently, δ -rays will have an impact on the cross section for single and multiple-bit upsets in sensitive technology nodes. Using stopping power, or LET, to determine the response

of a technology to a given single-event may not be adequate when considering the sensitivity of these devices to such abundant secondary particles as δ -rays.

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