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MULTI-SCALE, MULTI-PHYSICS MODELING AND SIMULATION OF SINGLE-EVENT EFFECTS AT DEVICE AND CIRCUIT LEVELS

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Abstract

This short-course aims to provide a state-of-the-art overview of modeling and simulation of single-event effects (SEEs) at device and circuit levels. It primarily focuses on the specific multi-scale, multi-physics, multi-domain nature of SEEs and on the main underlying physical mechanisms that lead to the occurrence of soft errors in digital circuits. In the first and main part of this contribution, a meticulous review will address the different ways to model and simulate both in space and time this complex sequence of mechanisms from the particle-material interaction up to the electrical response of a given circuit. In a second part, the text will present some specifics of modern technologies subjected to SEEs in terms of material diversity, device architectures and circuit layout complication. This short-course will conclude by an overview of works and challenges ahead to anticipate the SEE susceptibility of future nano-devices and related circuits.

1. Introduction

Single-event effects (SEEs) designate a set of physical and electrical phenomena that take place in a microelectronic device, component, subsystem, or system (digital or analog) impacted by a single energetic particle and that result in any measurable or observable change in its state, operation, or performance. SEEs were reported for the first times in the 1950s during nuclear weapon testing and observed in space electronics from the 60s. Terrestrial cosmic-rays (atmospheric radiation) and traces of radioactive impurities (alpha-particle emitters) in circuit materials were identified later in the 70s as the two major sources of SEEs at ground level. In the 80s, the interaction of low-energy (thermal) cosmic-ray-induced neutrons with the ^{10}B isotope of boron potentially present in circuit materials was also identified as another major source of SEEs.

In recent decades, the increasing importance of SEEs in modern electronics reliability has its origin in the extreme miniaturization of microelectronics devices (and its consequences on the electrical point-of-view concerning their operation) that has rendered them more and more sensitive to natural or artificial radiation in general and up to the most tenuous levels, as encountered for example at terrestrial ground level.

Alongside the experimental aspects, modeling and simulation has long been used for better understanding the radiation effects on the operation of devices and circuits. Because of its increasingly predictive capacity, which goes hand in hand with the power of computational tools and advances in physical modeling, simulation offers the possibility to reduce radiation experiments and to test hypothetical devices or conditions, which are not feasible (or not easily measurable) by experiments. For the study of SEEs in future devices for which experimental investigation is still limited, numerical simulation is an ideal investigation tool for providing physical insights and predicting the operation of future devices expected for the end of the roadmap.

2. Understanding the nature of the SEE problem

2.1. Definitions and classification

We start by a general definition of a Single-Event Effect, followed by a classification of the different types of SEEs.

- A Single-Event Effect is initiated by the passage of a single energetic particle through the volume of an electronic device.
- The striking particle may be an elementary particle (proton, neutron, muon, electron), an ion (alpha particle, heavy ion) or eventually a photon (gamma ray flash) capable of causing direct or indirect ionization.
- A SEE is created if the result of the interaction of the particle with the device or circuit interferes with its electrical operation, causing or not an observable functional error.
- A SEE can result in a reversible (non-permanent) or irreversible (permanent) change in device or circuit operation. In the first case, the error is recoverable and is qualified of "soft error"; in the second case, the error is generally the result of an unrecoverable damage and one speak about "hard error".

The recent revision of the JEDEC standard N°89B [1] proposes a definition and a classification of the different types of SEEs, resulting of several years of discussion and effort to try to standardize this ensemble of technical terms. They are summarized in Fig. 1 and their definition, according to the JEDEC standard, are given below (all quotes in italics correspond to definitions directly taken from [1]).

Soft errors (SE) include single-event transients (SET), single-event upsets (SEU), single-bit upsets (SBU), single-cell upsets (SBU), multiple-bit upsets (MBU), multiple-cell upsets (MCU), single-event functional interrupts (SEFI), single-event transients (SET) that, if latched, become SEU [1]:

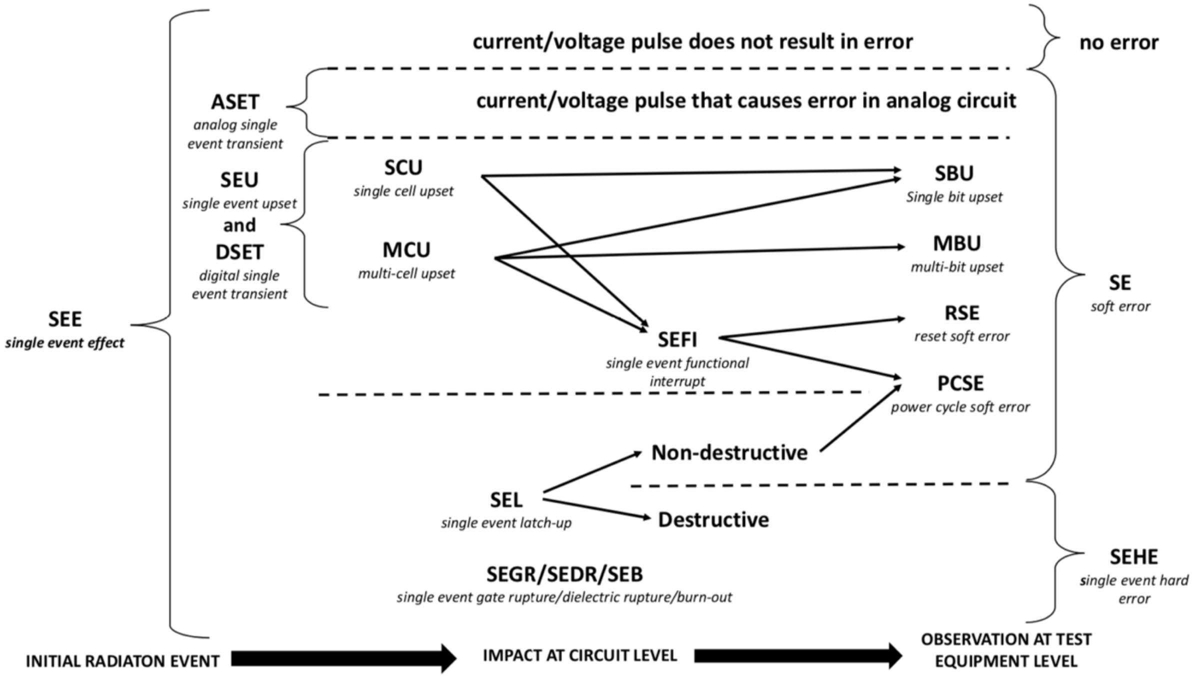

Figure 1. Diagram of terms used to describe single event effects. (After JEDEC Standard JESD89B [1]. © (2021) JEDEC.)

- Single-event upset (SEU): "*A non-permanent error caused by a state change of a latch, flop, memory cell or other bistable element from the particle strike. The energetic strike can occur directly on the circuit element or propagate to that circuit (see SET).*"
- Single bit upset (SBU): "*A SEU in which the observed error is a single logical or data bit.*"
- Single cell upset (SCU): "*A SEU where only one cell or logic element (latch, flip flop, etc.) is upset (compare to MCU).*"
- Multiple-bit upset (MBU): "*A single event that induces upset of multiple-cells where two or more of the upsets occur in the same logical word (or frame/column/sector, etc. for FPGAs). NOTE An MBU is a logical manifestation of a single event.*"
- Multiple-cell upset (MCU): "*A single event that induces several cells (e.g. memory cells or flip-flops) in an IC to flip their state at one time.*"
- Single-event functional interrupt (SEFI): "*A single event that causes the component to reset, lock-up, or otherwise malfunction in a detectable way, but does not result in permanent damage (i.e. hard error). Note that a SEFI is often associated with an SBU/MBU in a control bit or register, whereas a SEL is caused by the turn-on of a parasitic thyristor. Many SEFI events can be cleared with a component reset operation. In cases where resetting some configuration registers requires a complete power cycle of the device, it can be difficult to distinguish between a SEFI and a SEL (see below). A SEFI event does not necessarily result in an extended increase in operational current like a high current SEL.*"

- Single-event transient (SET): "*A time dependent radiation induced spurious current or voltage signal on a circuit node. A digital SET (DSET) occurs when an SET in a combinational logic gate (along data or control paths) propagates and is latched to create an error in the output of a sequential element. An analog SET (ASET) is a spurious signal in an analog circuit (e.g. a spurious signal on an IO pin, etc.) that causes an erroneous output.*"

Single Event Hard errors (SEHE) include single event gate oxide ruptures (SEGR), single event dielectric ruptures (SEDR), single event burn-outs (SEB) and destructive single event latchups (SEL) [1]:

- Single-event gate rupture (SEGR): "*An event in which a single energetic particle strike results in a breakdown and subsequent conducting path through the gate oxide of a MOS transistor.*"
- Single-event dielectric rupture (SEDR): "*An event in which conducting path is created in a dielectric material from a single energetic particle strike.*"
- Single-event burnout (SEB): "*An event in which a single energetic particle strike induces a localized high-current state in a device, resulting in catastrophic failure.*"
- Single-event latchup (SEL): "*An abnormal current state in a circuit caused by the passage of a single energetic particle inducing a parasitic thyristor to turn on and remain in a fixed state regardless of inputs, until the device is power cycled. Some SEL events result in a measurable current increase (e.g. latch-up of an IO circuit). Some SEL events may result in a difficult to detect increase in current (micro-SEL) compared to the quiescent current of the entire component (e.g., latchup of memory cells within a common well). A high current SEL may cause permanent damage to the component and result in a hard error. Micro-SEL events are typically non-destructive due to the low current draw and can be cleared by power cycling.*"

2.2. Main steps to produce a SEE in a circuit (summary)

Before surveying the main modeling and simulation approaches of SEEs and going into the substance of several underlying mechanisms for creating SEEs, we summarize in the following and in Fig. 2 the main steps leading to the production a SEE in a circuit.

1) Interaction of the incoming particle with the target material

A SEE is always initiated by the interaction of an incident particle with the target material. This interaction necessarily involves a transfer of energy from the particle to the medium via electromagnetic or nuclear processes. As a result of such processes, a fraction or the totality of the incoming particle energy is released inside the medium [2]. We distinguish at this level two main interaction processes for the usual particles susceptible to be at the origin of SEEs in electronics: the direct ionization and the indirect ionization of matter.

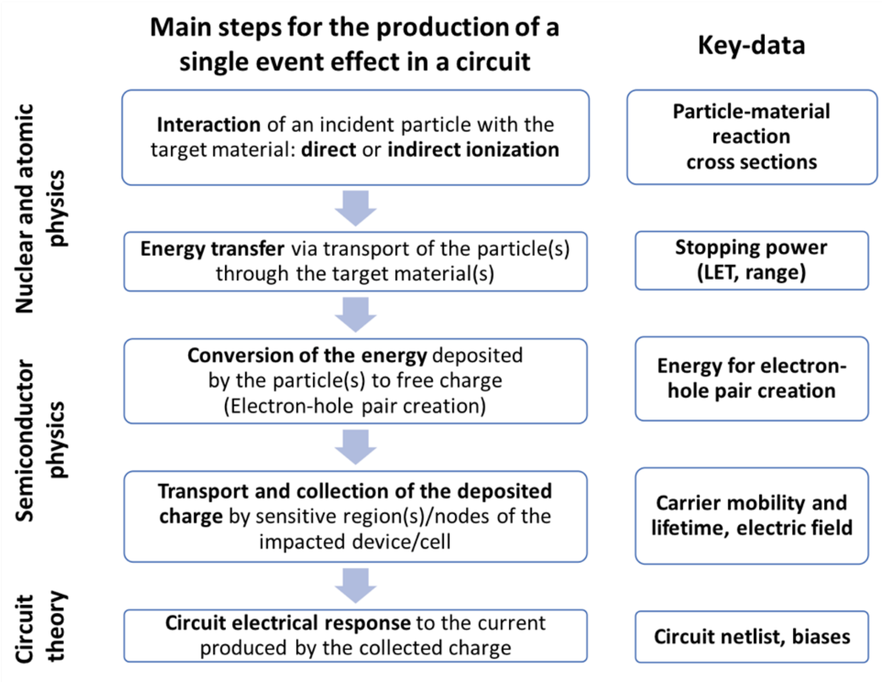

Figure 2. Main steps to produce SEEs and key-data considered for their modeling and simulation.

- Direct ionization: for electrons, muons, low energy protons (E< 1 MeV), alpha particle and heavy ions (with atomic number Z>1), these particles mainly interact with the electrons and nuclei of the target material [3]. In the initial phase of the passage of such a charged particle in matter, collisions with atomic electrons are the principal mode of energy loss in a very wide range of energies of the incident particle. These interactions gradually slow down the particle. In the final phase, the particle slowing and stopping are due to collisions with nuclei. The ionization induces the generation of a large number of excited energetic electrons (delta-rays) which generally have sufficient energy to ionize other atoms. An electronic cascade is activated in which the number of free electrons continues to increase while their average energy decreases. During the passage of the ionizing particle, a highly ionized channel of very small diameter (typically a few tens of nm) develops around the track of the particle. Very rapidly, the excited electrons in the plasma are losing their kinetic energy in excess by a series of elastic collisions with electrons of the lattice to finally reach an energy close to the binding energy of the material. Simultaneously, the ionized atoms, positively charged, rearrange their electrons resulting in creation of holes in the valence band. A high-density column of electron-hole pairs is then formed in a narrow region around the particle track [3].

- Indirect ionization: for neutrons and high-energy protons (E > 10 MeV), these particles can interact only with atomic nuclei following two major mechanisms, i.e., scattering (elastic, inelastic) and capture (or nonelastic). In the former case, the total kinetic energy is conserved, and the incoming neutron or proton is deflected from its path as it transfers some of its energy to the target atom. In the latter case of inelastic scattering, the target nucleus rearranges its internal state to one of higher energy, and the total kinetic energy is not conserved. But in both cases, there is only one outgoing neutron or proton and the nature of the recoil nucleus is left unmodified. Instead of being scattered, an incident neutron or proton may be absorbed or captured by a target material nucleus. After it has absorbed the impinging particle, the nucleus can get rid of excess protons or neutrons, it can undergo de-excitation by emitting a γ-ray, or it may even split in medium-sized fragments when the energies are high enough to trigger nuclear fission (it exists a threshold energy for each reaction). The produced fragments extend from proton or neutron to the nucleus of the target atom; they can in their turn directly ionize the matter like any charged particle (previous case).

The number of nuclear interactions per type of interaction can be evaluated from cross section data of the atom nuclei present in the target material. For monoenergetic neutrons or protons arriving perpendicularly on a thin sheet of natural material, the number of nuclear interactions occurring in the target is given by:

$$N_X(E) = \sum_i f_i \sigma_{X,i}(E) \times 10^{-24} \times NV \times e \times M \tag{1}$$

where X is the type of the considered interactions (elastic, inelastic, nonelastic), E is the energy of the incident neutrons or protons, $\sigma_{X,i}(E)$ is the value at energy E of the type X reaction cross section for isotope i (expressed in barn), f_i is the fraction of isotope i in the target isotopic composition, e is the target thickness (expressed in cm), NV is the number of atoms per cubic centimeter and M is the number of incident monoenergetic neutrons or protons impacting the target.

2) Energy transfer from the ionizing particle(s) to the target material

Whether direct or indirect ionization, two key-quantities are defined to characterize the energy transfer from an ionizing particle[1] to the target material: the stopping power and the range. We recall below the definitions of these two quantities.

- Stopping power: The stopping power is the amount of energy lost by a particle in the matter per unit length. It is usually expressed in keV/µm or MeV/µm. The total stopping power is decomposed into two components: i) the electronic stopping power, corresponding to the loss of energy of the particle due to collisions with atomic electrons of the target material; ii) the nuclear stopping power, corresponding to the loss of energy of the particle due to collisions with the nuclei of atoms of the target material. The electronic stopping power is also called Linear Energy Transfer (LET). The LET thus characterizes the creation of electron-hole pairs by ionization of the target material, while nuclear stopping power describes the atomic displacement of the target material [3]. The LET is expressed as:

$$LET = -\frac{\Delta E}{\Delta x} \tag{2}$$

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[1] i.e., an incident ionizing particle penetrating into the target material or produced as a secondary particle in an interaction event involving a primary incoming particle and a target atom nucleus.

where *ΔE* represents the energy loss per unit length *Δx*. For a nonrelativistic charged particle with speed v, charge z (in multiples of the electron charge) traveling into a target of electron density n and mean excitation potential I, its LET can be analytically evaluated from the reduced form of the Bethe-Bloch formula [4]:

$$LET = \frac{4\pi n z^2}{m_e v^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[ln\left(\frac{2m_e v^2}{I}\right)\right] \tag{3}$$

where ε_0 is the vacuum permittivity, e and m_e are the electron charge and rest mass respectively. (3) shows that LET increases with decreasing particle velocity until it reaches a maximum value where it goes to zero. A weighted LET is generally used, defined as the ratio between the LET and the density ρ of the target material:

$$LET = -\frac{1}{\rho}\frac{\Delta E}{\Delta x} \tag{4}$$

The unit of this weighted LET is MeV/(mg/cm^2).

- Range: The range R is the distance traveled by a ionizing particle of initial kinetic energy E_0 before it comes to rest in the stopping material; it is calculated from the LET of the particle as:

$$R(E_0) = \int_{E_0}^{0} -\frac{1}{\frac{dE}{dx}} dE = \int_{0}^{E_0} \frac{1}{LET} dE \tag{5}$$

3) Conversion of the deposited energy to an electrical charge

The conversion of the energy deposited by an ionizing particle to free charge in a given target material can be evaluated from its mean value of energy for electron-hole pair creation $E_{e,h}$, a material-dependent constant usually experimentally measured or determined via Full-band Monte Carlo Simulations (see for example a recent work performed for bulk silicon and germanium [5]). When experimental or accurate simulated values are not available for a given semiconductor material, $E_{e,h}$ can be estimated from the Klein's phenomenological model that establishes a linear relationship between the bandgap energy and $E_{e,h}$ in semiconductor materials [6]:

$$E_{e,h}(eV) \simeq \frac{14}{5} E_g(eV) + 0.66 \tag{6}$$

The well-known value for bulk silicon is $E_{e,h}$ = 3.6 eV at 300 K. From (3), $E_{e,h}$ is expected to vary from ~1.1 eV for InSb (E_g = 0.17 eV at 300 K) to ~12 eV for diamond (E_g = 5.47 eV at 300 K).

For a given target material characterized by its density ρ and its average energy for electron-hole pair creation $E_{e,h}$ and considering a particle with a given LET value, it is possible to calculate the charge deposited by this particle along a path of length ℓ in the target material from the following expression:

$$Q_{dep}\,[fC] = \frac{16.02 \times \rho\,[g/cm^3]}{E_{e,h}\,[eV]} \times LET\,[MeV/(mg/cm^2)] \times \ell\,[\mu m] \qquad (7)$$

This value is even more precise as the product LET×ℓ is small because the LET value varies when the particle progresses in the material.

4) <u>Transport and collection of the deposited charge in the region of the impacted circuit</u>

Once a very dense column of electron-hole pairs has been created almost instantaneously[2] along the track of the ionizing particle, this deposited charge rapidly evolves under the action of different mechanisms that control the charge-carrier dynamics, e.g., its transport in the semiconductor material and its possible collection by a circuit node.

- Charge transport: the development of the column of electron-hole pairs starts in the femto-second range after its creation following three mechanisms that contribute to the reduction of the density of excess carriers at the heart of the track: ambipolar diffusion, carrier recombination (Shockley-Read-Hall and Auger recombination) and separation between holes and electrons under the combined effect of diffusion and drift induced by local electrical fields [7]. Released charges from this plasma column and having escaped the initial massive recombination are quickly transported further into the semiconductor by diffusion and also by additional drift in regions where a non-zero electric field exists.

Charge collection: Released charges in the "vicinity" of a circuit node at front-end-of-line (FEOL) level, e.g. near or across a reversely-biased p-n junction or a biased diffused area contact, can be collected via drift-diffusion by such a structure and be extracted from the semiconductor material to the circuit. This charge collection process is crucial in the formation of a parasitic transient current that is injected on the impacted node. We will come back in detail in Section 3 on the physics, modeling, and simulation aspects of this key-step in the formation of SEEs. Fig. 3 illustrates the charge transport and collection in the case of a neutron-silicon nuclear reaction occurring in the volume of the space charge region (SCR) of a reversely biased nano-transistor drain junction and producing four ionizing secondaries. This illustration is the result of a simplified particle Monte Carlo simulation in which the radiation-induced minority carriers (here the electrons grouped per packets of multiple charges) are represented by red points. After the production of secondaries and the energy deposition along their tracks (Fig. 3-1), the widening of the charge clouds reflects the diffusion of the carriers, their displacement towards the top surface, their drift in the electrical field (here vertical) of the junction (Figs. 3-2, 3, 4).

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[2] The practically instantaneous delivery of the ion energy to the electronic subsystem of a solid, lasting from 0.1 to 10^3 fs, creates a large number of electron-hole pairs per unit track length. [7]

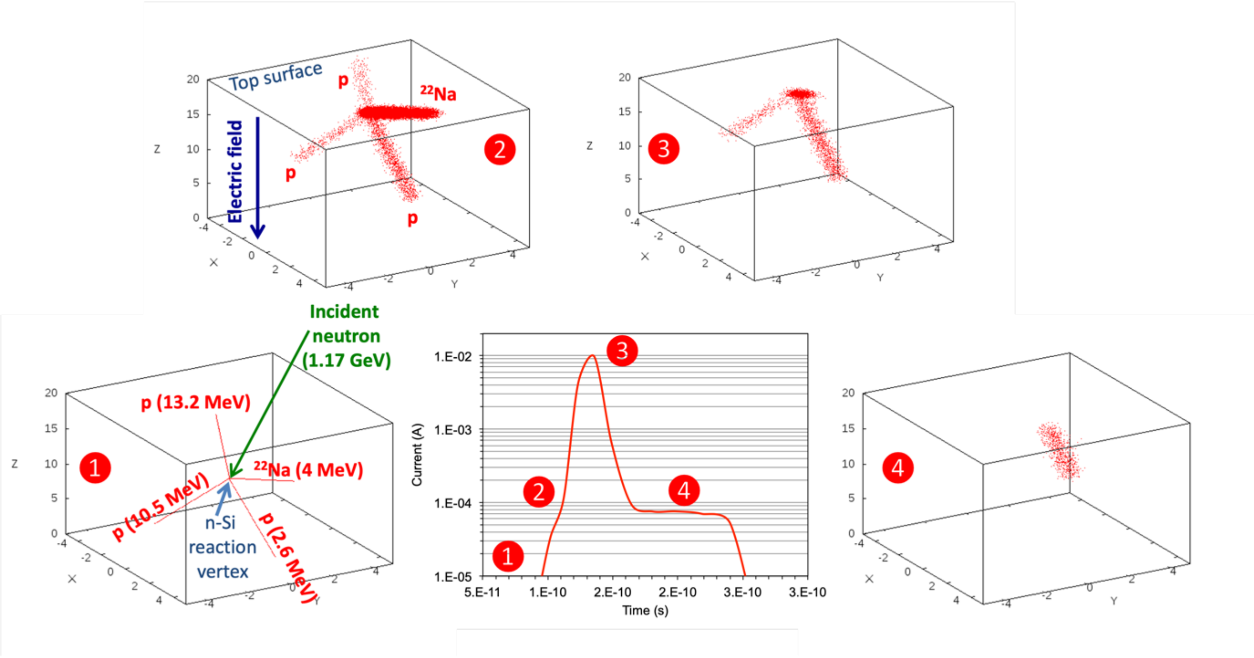

Figure 3. Particle random-walk drift-diffusion numerical simulation (described in section 3.3.2) of charge generation, transport and collection phases in a reverse-biased junction caused by the interaction of a 1.17 GeV neutron with a silicon atom (3 protons and a ^{22}Na ion produced). The transient current extracted from the junction contact (corresponding to the top surface) is also plotted. Dimensions on the three axes are in nanometers.

Carriers are finally extracted from the top surface (electrode) where they contribute to the formation of the transient current that is injected into the external circuit.

5) <u>Circuit electrical response</u>:

The current transient pulse resulting from the radiation-induced charge collection and extraction at the level of a circuit node may induce disturbances in the circuit to which the impacted node is connected. The induced effects at circuit level are different according to the intensity of the current transient, as well as the number of impacted circuit nodes. If the transient peak is sufficiently important in terms of current magnitude, it can induce a hard error (permanent damage) on gate insulators (gate rupture, SEGR) or provoke a short-circuit loop between different semiconductor regions (latchup, burnout). In other cases, the transient current may generally induce a soft error which can be manifested by the change of logic state of one or more memory points (upset) or even a functional interrupt. In the following (section 3), we will examine in detail the circuit electrical response to such radiation-induced pulses and we will show that the circuit is not necessary passive during this phase of charge collection. On the contrary, it can play an important role via the counter-reaction it develops on the impacted node potential following the collection of charges on it.

2.3. Multi-physics, multi-scale and multi-domain nature of SEE

The previous subsection summarized the different stages of production of an SEE in a circuit. It shown that single-event effects are inherently multi-physics, multi-scale and multi-domain, as indicated in the following.

- Multi-physics: SEEs are first initiated by particle-matter interactions, fields of nuclear and atomic physics. Then, they involve the creation of charges and their transport in materials, mainly semiconductors, governed by solid-state physics and quantum-mechanics. The resulting transient current or voltage pulse created in the interconnected network of elementary structures that constitute the circuit itself, in the sense of the electronics function, obeys the fundamental laws of electrokinetics and circuit theory. Finally, the potentially disturbed circuit response can affect the system of which it is a part, governed by the general theory of systems.

- Multi-scale: SEEs are initiated by a single particle interaction at atomic-level in the bulk of circuit materials and can lead to a functional error at circuit or system-level. Between these two events, there are approximately 15 orders of magnitudes on the distance scale and approximately 20 orders of magnitude on the time scale. In addition to the multi-physics nature of SEEs, these changes of scale both in time and in distance explain the impossibility of simulating SEEs with a single tool from the beginning to the end of this sequence of events.

- Multi-domain: SEE, or more accurately the precursor event to a SEE, is first of all an atomic event before being transformed into an electrical signal then into an analog or logical event. Depending on when it is considered, it therefore belongs to different fields or domains: the domain of materials, then of devices, then of circuits and finally of systems. To each domain corresponds a particular expression of this SEE precursor: secondary particles of a nuclear interaction, bundle of electron-hole pairs, transient current, analog signal, logic pulse, value encoded in a memory, etc. When passing from a domain to the next following the SEE chronology, the physics of the previous domain is lost in the new domain. For example, when the secondary particle energy is converted in e-h pairs, the nuclear physics becomes useless to continue to describe the formation of the SEE and any information relating to the nuclear event is moreover lost. This vision is true until the expression of the SEE at the system or application level, at the end of the chain.

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