Radiation and COTS at ground level

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ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form 20 June 2015
Accepted 21 June 2015
Available online xxxx

Keywords:
Single event effects (SEE)
Radiation effects
CMOS technologies
Components Off the Shelf (COTS)
Terrestrial cosmic rays
Neutrons
Protons
Accelerated tests
Real-time tests
Modeling and simulation
CMOS bulk
FD-SOI
FinFET

ABSTRACT

This tutorial surveys single event effects (SEE) induced by terrestrial cosmic rays on current commercial CMOS technologies. After describing the natural radiation environment at ground and atmospheric levels, the tutorial describes the physics of SEEs, from the main mechanisms of interaction between atmospheric radiation (neutrons, protons, muons) and circuit materials to the electrical response of transistors, cells and complete circuits. SEE characterization using accelerated and real-time tests is examined, as well as modeling and numerical simulation issues. Special emphasis finally concerns the radiation response of advanced technologies, including deca-nanometer bulk, FD-SOI and FinFET families.

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1. Introduction

Microelectronics industry has experienced tremendous progress in the last forty years, especially with regard to the evolution of the product (i.e. integrated circuits) performances, and at the same time, concerning the drastic reduction of manufacturing costs per elementary integrated function. So far, this considerable growth of the semiconductor industry has been due to its technological capability to constantly miniaturize the elementary components of circuits, namely the MOSFET (metal-oxide-semiconductor field effect transistor), the basic building block of VLSI (very large scale integration) integrated circuits. However, the conventional bulk MOSFET scaling encountered in this last decade serious physical and technological limitations, mainly related to the gate oxide (SiO₂) leakage currents [1], the large increase of parasitic short channel effects and the dramatic mobility reduction [2] due to highly doped silicon substrates necessarily used to reduce these short channel effects. Technological solutions have been proposed in order to continue MOSFET miniaturization, such as: (i) the introduction of high-permittivity gate dielectric stacks [3], midgap metal gate and strained silicon channels [4]; (ii) the replacement of the conventional bulk MOSFET architecture by alternative solutions including the use of new materials (e.g. SOI materials) or new device architectures (e.g. Multiple-Gate devices [5], silicon nanowire MOSFETs) allowing better electrostatic control, and, as a result, intrinsic channels with higher mobilities and currents.

As MOSFET scales have reduced, the sensitivity of the integrated circuits to radiation coming from the natural space or present in the terrestrial environment has been found to seriously evolve [6–8]. Nowadays, for ultra-scaled devices, natural radiation is inducing one of the highest failure rates of all reliability concerns for devices and circuits in the area of nanoelectronics [7]. In particular, ultra-scaled memory integrated circuits have been found to be more sensitive to single-event-upset (SEU) and digital devices more affected by digital single-event transient (DSETs). This sensitivity is a direct consequence of the reduction of device dimensions and spacing within memory cells combined with the reduction of supply voltage and node capacitance, resulting in a decrease of both the critical charge (i.e. the minimum amount of charge required to induce the flipping of the logic state) and the sensitive area (i.e. the minimum collection area inside which a given particle can deposit enough charge to induce a change in the cell) [7,9].

This tutorial is structured in four main sections. In Section 2, we will briefly describe the natural radiation environment at ground and...
atmospheric levels. The physics of SEEs will be summarized in Section 3, from the main mechanisms of interaction between atmospheric radiation (neutrons, protons, muons) and circuit materials to the electrical response of transistors, cells and complete circuits. Section 4 will explain SEE characterization using accelerated and real-time tests, as well as modeling and numerical simulation issues. Finally, Section 5 will present and discuss the radiation response of advanced commercial technologies, including deca-nanometer bulk, FD-SOI and FinFET families.

2. Radiation environments vs. applications (space, atmospheric and ground level)

Single event effects (SEE) are the result of the interaction of highly energetic particles, such as protons, neutrons, alpha particles, or heavy ions, with the sensitive region(s) of a microelectronic device or circuit. A single event may perturb the device/circuit operation (e.g., reverse or flip the data state of a memory cell, latch, and flip-flop) or definitively damage the circuit (e.g. gate oxide rupture, destructive latch-up events). The problem has been well known for space applications over many years (more than forty years) and production mechanisms of SEE in semiconductor devices by energetic protons or heavy ions well apprehended, characterized and modeled [10]. In a similar way for avionic applications, the interaction of atmospheric neutrons (and to a lesser extend protons) with electronics has been identified as the major source of SEE [11]. For the most recent deca-nanometer technologies, the impact of other atmospheric particles produced in nuclear cascade showers on circuits has been clearly demonstrated, in particular low-energy protons [12] and more recently atmospheric low energy muons [13].

With respect to such high-altitude atmospheric environments, the situation at ground level is slightly different (Fig. 1). Of course, atmospheric neutrons are always the primary particles but, with a flux approximately lower by a factor ~300 at sea-level with respect to the flux at avionic altitudes, the soft error rate (SER) of circuits can be now affected by other additional sources of radiation: the alpha particles generated from traces of radioactive contaminants in CMOS process or packaging materials [14,15] and the low energy (<1 GeV) atmospheric muons. As a consequence of these multiple sources of radiation, the accurate modeling and simulation of the SER of circuits at ground level are rather a complex task because one can clearly separate the contribution to SER of atmospheric particles (the external constraint) from the one due to natural alpha-particle emitters present as contaminants in circuit materials (the internal constraint). We briefly detail in the following these two natural radiation constraints at ground level.

2.1. Atmospheric radiation

A complex cascade of elementary particles and electromagnetic radiation is generally produced in the Earth's atmosphere when a primary cosmic ray (of extraterrestrial origin) interacts with the top atmosphere [16]. The term cascade means that the incident particle (generally a proton, a nucleus, an electron or a photon) strikes a molecule in the air so as to produce many high energy secondary particles (photons, electrons, hadrons, nuclei) which in turn create more particles, and so on.

Among all these secondary particles, neutrons represent the most important part of the natural radiation affecting ground level susceptibility for current electronics. Because neutrons are not charged, they are very invasive and can penetrate deeply in the circuit materials. They can interact via nuclear reactions with the atoms of the target materials and create (via elastic or inelastic processes) secondary ionizing particles. This mechanism is called "indirect ionization" and is potentially an important source of errors induced in electronic components. One generally distinguishes thermal neutrons (interacting with 19B isotopes potentially present in circuit materials, but progressively removed from technological processes [7]) and high-energy atmospheric neutrons.

![Fig. 1. Differential flux (up) and integral flux (down) of cosmic-ray induced neutrons measured on the roof of the IBM T. J. Watson Research Center in Yorktown Heights (NY) using an extended-energy Bonner sphere spectrometer [17]. Numerical data courtesy of P. Goldhagen.](image-url)
(up to the GeV scale). Fig. 1 (top) shows the typical energy distribution of atmospheric neutrons at ground level, as measured using an extended-energy Bonner sphere spectrometer [17]. This distribution ranges from thermal energies to several tens of GeVs. The integration of this spectrum gives the total neutron flux expressed in neutrons per square centimeter and per hour (Fig. 1 bottom). At sea level (New York City), this flux is equal to 7.6 n/cm²/h below 1 eV (thermal and epithermal neutrons), 16 n/cm²/h for the intermediate part (between 1 eV and 1 MeV) and 20 n/cm²/h for the upper part (high energy neutrons above 1 MeV) [18]. This last value is reduced to 13 n/cm²/h when integrating the flux above 10 MeV [18]. The total neutron flux over the whole energy range (from thermal to high energies) is equal to 43.6 n/cm²/h for this location and measurement conditions reported in [17].

Atmospheric muons also represent an important part of the natural radiation at ground level [16]. Muons are the products of the decay of secondary charged pions (p±) and kaons (K±). In spite of a lifetime of about 2.2 μs, most of muons survive to sea level due to their ultra-relativistic character. They are the most abundant particles at sea level with a total (μ− + μ+) integrated flux above 1 MeV of around 60 μ/cm²/h, as estimated using the EXPACS model [19] (Fig. 2) or QARM models. High-energy physicists are familiar with an order of magnitude of one particle per cm² and per minute for horizontal detectors. This corresponds to ~70 m⁻² s⁻¹ sr⁻¹ above 1 GeV. But despite this abundance, muons interact very weakly with matter, excepted at low energies (typically below 1 GeV) by direct ionization. The relative importance of low energy muons in the SER of the most advanced CMOS technologies will be discussed in Section 5.

In contrast and while strongly interacting with matter, pions are not sufficiently abundant at ground level to induce significant effects in components. Furthermore, for modern technologies, the small amount of electrons and gamma rays with low energies (susceptible to interact with matter) is not able to disrupt electronics.

Finally, protons, although they interact with silicon as neutrons typically above 50–100 MeV, they are one hundred times less numerous than the latter at ground level (Fig. 2). Their low abundance at sea level (1.5 proton cm⁻² h⁻¹) allows us to consider their impact as negligible compared to that of neutrons, except at low energies (<1 MeV) for which certain advanced technologies show an exacerbated sensitivity due to charge deposition by direct ionization. In contrast, for avionic applications, the number of protons is ~500 times higher than at ground level and they constitute a non-negligible component of the atmospheric radiation constraint for electronics.

2.2. Telluric radiation sources

Any terrestrial material contains traces of radioactive atoms, in a wide range varying from a few atoms on thousands for the most active materials to a few atoms per tens of billions for the most purified ones. These natural radioisotopes contained in the Earth’s crust are the principal natural sources of α, β and γ radioactivities but only the alpha-particle emitters present a reliability concern in microelectronics. Beta and gamma processes are indeed not able to deposit a high enough amount of energy to significantly impact the microelectronic circuit operation. On the contrary, alpha-particles (He²⁺) produced by radioactive decay with typical energies ranging from 1 to 10 MeV can cause a sudden burst of several millions of electrons in silicon over a path of a few tens of microns. This is generally sufficient to induce a transient current that can disturb the operation of a given integrated circuit.

Radioactive nuclei can be classified into two categories: the "radioactive materials" and the “radioactive impurities” or pollutants [20]. Radioactive materials naturally contain a proportion, generally weak, of alpha-emitter isotope, as for example hafnium (179/Hf) is an alpha emitter, its natural abundance is 0.162%). The second category corresponds to an unwanted element, i.e. unintentionally introduced during the process. This mainly corresponds to uranium and thorium, which have alpha emitter isotopes in their respective disintegration decay chain. Th²³² and U²³⁸ are widely present in the natural environment and can easily pollute water flow and raw materials used at wafer, packaging and interconnection levels.

Considering the activity of radioisotopes in the calculation of the soft error rate of a circuit thus requires accurate modeling of the alpha-particle source mimicking the presence of these alpha-particle emitters in the circuit materials. For example, considering traces of uranium in a given material (silicon for example) requires taking into account the complete uranium disintegration chain composed of 14 daughter nuclei with 8 alpha-particle emitters [21]. The energies of these alpha particles range from 4.20 to 7.68 MeV; their corresponding ranges in silicon vary from 19 to 46 μm and their initial Linear Energy Transfer (LET) from 0.47 to 0.68 MeV/(mg/cm²).

3. SEE production at silicon level

The physical mechanisms related to the production of SEE in microelectronic devices schematically consist of successive steps, illustrated in Fig. 3 in the case of an alpha particle striking a reverse-biased n+/p junction [22]: (1) the charge deposition by the energetic particle within the sensitive region, (2) the transport of the released charge into the device and (3)–(4) the charge collection in the active region of the device. In the following, we succinctly describe these different mechanisms, for a detailed presentation we invite the reader to consult ref. [6,7].

3.1. Charge deposition (or generation)

When an energetic charged particle strikes the device, an electrical charge along the particle track can be deposited by one of the following mechanisms: direct ionization by the interaction with the material or indirect ionization, by secondary particles issued from nuclear reactions with the atoms of the struck material. Direct ionization by heavy ions (Z ≥ 2) of the space environment is particularly important. These interact with the target material mainly by inelastic interactions and transmit a large amount of energy to the electrons of the struck atoms.

![Fig. 2. Integral flux (E > 1 MeV) for atmospheric neutrons, protons, muons and electrons as a function of the altitude for the geographic coordinates (42° N 72° W) corresponding to New York City. Data obtained using the EXPACS model [19].](image-url)
These electrons produce a cascade of secondary electrons which thermalize and create electron–hole pairs along the particle path [Fig. 3(1)]. In a semiconductor or insulator, a large amount of the deposited energy is thus converted into electron–hole pairs, the remaining energy being converted into heat and a very small quantity into atomic displacements. It was shown experimentally that the energy necessary for the creation of an electron–hole pair depends on the material bandgap. In a microelectronics silicon substrate, one electron–hole pair is produced for every 3.6 eV of energy lost by the ion. Other particles, such as the neutrons of the terrestrial environment, do not interact directly with the atomic electronics of the target material and so do not ionize the matter on their passage. However, these particles should not be neglected, because they can produce SEE due to their probability of nuclear reaction with the atoms of materials that compose the microelectronic devices. This mechanism is called indirect ionization. The charged products resulting from a nuclear reaction can deposit energy along their tracks, in the same manner as that of direct ionization. Since the creation of the column of electron–hole pairs of these secondary particles is similar to that of ions, the same general models and concepts can be used.

### 3.2. Charge transport

When a charge column is created in the semiconductor by an ionizing particle, the released carriers are quickly transported and collected by elementary structures (e.g. p-n junctions). The transport of charge relies on two main mechanisms [Figs. 3(2) to (4)]: the charge drift in regions with an electric field and the charge diffusion in neutral zones. The deposited charges can also recombine with other mobile carriers existing in the lattice.

### 3.3. Charge collection

The charges transported in the device induce a parasitic current transient [Fig. 3 bottom], which can induce disturbances in the device and associated circuits. The devices most sensitive to ionizing particle strikes are generally devices containing reversely-biased p-n junctions, because the strong electric field existing in the depletion region of the p-n junction allows a very efficient collection of the deposited charge. The effects of ionizing radiation are different according to the intensity of the current transient, as well as the number of circuit nodes impacted. If the current is sufficiently important, it can induce permanent damage on gate insulators (gate rupture, SEGR) or the latch-up (SEL) of the device. In usual low-power circuits, the transient current may generally induce only an eventual change of the logical state (cell upset).

### 4. SEE characterization and modeling issues

#### 4.1. SEE characterization using accelerated and real-time tests

To predict the impact of natural radiation on the behavior of electronics and to (statistically) estimate (measure) its radiation-induced soft error rate (SER), three main experimental methods can be envisaged [14,23], excluding modeling and simulation approaches that can be used, under certain conditions (i.e. when correctly calibrated), as predictive tools (see Section 4.2).

The first one, called “field testing”, consists of collecting errors from a large number of finished products already on the market. The SER value is evaluated a posteriori from the errors experienced by the consumers themselves; it takes generally several years after the introduction of the product on the market. This method is not adapted to upstream...
reliability studies performed during the cycle of product development and will not be considered in the following.

The second method, called “accelerated” soft error rate (ASER), consists of using intense particle beams or sources chosen for their capability to mimic the atmospheric (neutron) spectrum or to generate alpha particles within the same energy range than the alphas emitted by radioactive contaminants [14,23]. Alternate solutions considering monoenergetic sources of particles are also frequently used for measuring the energy dependence of the single–event effects. Details about atmospheric-like or monoenergetic sources of neutrons can be found in [23]. A complete list of facilities can be also found in the Compendium of International Radiation Test Facilities [24]. This accelerated SER (ASER) method is fast (data can be obtained in a few hours or days instead of months or years for the other methods), a priori easy to implement and only requires a few functional chips to estimate the SER. This allows the manufacturer to perform such radiation tests relatively early in the production cycle. Another major and growing advantage is its capability to quantify from a very large statistics (cumulated number of events) the importance of multiple cell/multiple bit upsets in the radiation response of ICs fabricated in technological nodes typically below 65 nm. But data can be potentially tainted by experimental artifacts (more or less well controlled according to the facility, the experimental setup or other various experimental conditions). As a direct consequence, ASER results must be extrapolated to use conditions and several different radiation sources must be used to ensure that the estimation accounts for soft errors induced by both alpha particle and cosmic-ray-neutron events.

The third method consists of exposing a given device (or a large number of identical devices) to terrestrial radiation over a sufficiently long period (weeks or months) in order to achieve adequate statistics on the number of accumulated errors and then on the SER value. This method is called “real-time” soft error rate (RTSER) test [25–27] or unaccelerated testing. In this method, as in accelerated testing, the intensity of the natural radiation can be increased by deploying the test in altitude (at least for neutrons). However, the acceleration factor (i.e., the ratio of the neutron integrated flux at the test location divided by its reference value at NYC [23]) has nothing to do with those reached in accelerated tests. Considering an equivalence of the radiation background composition in altitude and at sea-level [23], typical values between 5 and 20 as a function of the test location on Earth, can be expected. Devices have thus been tested for a long enough period of time (months or years) until enough soft errors have been accumulated to give a reasonably confident estimate of the SER. The main advantage of RTSER tests is that they provide a direct measurement of the “true” SER that does not require intense radiation sources and extrapolations to use conditions. The major drawbacks of this method concern the cost of the system (which has to be capable of monitoring a very large number of devices at the same time) and the long duration of the experiment.

Fig. 4 summarizes these three different approaches in the form of a two-dimensional chart, qualitatively highlighting test specificities of each approach [27]. It highlights the fundamental differences between RTSER and ASER test strategies, notably in terms of test duration, number of devices, test cost, test setup complexity and experimental artifacts.

4.2. Modeling issues

Modeling and simulating the effects of ionizing radiation have long been used for better understanding radiation effects on the operation of devices and circuits. In the last two decades, due to substantial progress in simulation codes and computer performances that reduce computation times, simulation has acquired significantly increased interest [28,29]. Due to its predictive capability, 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. The continuous reduction of the feature size in microelectronics requires increasingly complicated and time-consuming manufacturing processes. Therefore, a systematic experimental investigation of the radiation effects of new ultra-scaled devices or emerging devices with alternative architecture (such as multiple-gate or silicon nanowire transistors) is difficult and expensive. Since computers today are considerably cheaper resources, simulation is becoming an indispensable tool for the device engineer, not only for the device optimization, but also for specific studies such as the device sensitivity when subjected to ionizing radiation. Last but not the least, the understanding of the soft error mechanisms in ultra-scaled devices and the prediction of their occurrence under a given radiation environment are of fundamental importance for certain applications requiring a very high level of reliability and dependability [14].

- **Device-level modeling approach.** Simulation of radiation effects at device-level aims to describe both the device (physical construction and electrical behavior) and its operation when it is subjected to a given type of radiation (heavy ions, alpha particles, etc.). Two methods can be used for this purpose, on the one hand the device numerical simulation (TCAD) and on the other hand the use of compact models (which are later included in circuit-level SPICE-like simulations). TCAD numerical modeling concerns both the simulation of the manufacturing process and the simulation of the device electrical operation. Concerning this last point, the electrical simulator solves the main differential physical equations, such as the Poisson equation and the transport and continuity equations. At this level, the effect of a particle strike is taken into account as an external generation source of carriers. The electron–hole pair generation induced by the particle strike is included in the continuity equations via an additional generation rate. In the particular case of neutrons that interact with matter by indirect ionization, these effects can be simulated with TCAD simulators by considering the different neutron reaction products (charged particles) in the simulation [30]. The main inconvenient of this TCAD simulation is the computation time, which can be very important depending on the simulation domain size and the equations considered for the transport (drift-diffusion, hydrodynamic). But the significant advantage of TCAD is the ability to access internal quantities of the simulation (which cannot be measured), which substantially facilitate the fine understanding of the physical and electrical mechanisms taking place in the device. In contrast to TCAD, compact models are based on analytical formulae that describe the static/dynamic electrical behavior of the elementary devices constituting the circuit. They literally constitute a bridge between the device (which is itself closely related to technology) and the circuit design.

- **Circuit-level modeling approaches.** Three main modeling approaches are used for the simulation of single-event effects at circuit-level: circuit-level simulation, mixed-mode and full numerical simulation in the 3-D device domain. This later currently remains the most accurate solution for studying SEE in circuits since it numerically
models and solves the entire impacted sub-circuit in the 3-D device domain. This was possible only recently (typically in the past decade), due to the enhancement of computer performances (CPU clock speed, memory resources), which reduced the computational time.

- **Monte Carlo simulation tools.** Full Monte Carlo-based physical simulations of the SER provide a very powerful way to bring much more detailed physics to bear on the process of error rate prediction than has heretofore been possible with models and analytical computations [31–33]. Schematically, Monte Carlo simulation codes solve the radiation problem in two main steps, the interaction of radiation with the device and the subsequent motion of charges, and resulting changes in nodal currents and/or voltages, within the device/circuit. The complete simulation chain is complex due to its multi-scale and multi-physics character. Several code developments have been reported in the literature in the domain of single event effects, see particularly ref. [32] for a recent review.

5. Radiation response of advanced technologies

While CMOS technologies continue to shrink in a “More Moore” perspective, new risks are arising with scaling for single event effects (SEE). Indeed, the SEE susceptibility of advanced technologies is expected to evolve under the influence of several factors since extrinsic radiation does not scale down. The most important are [34,35]: 1) the reduction of the critical charge, 2) the reduction of the per-bit cross-sections presented to ionizing particles, 3) the reduction of the energy-deposition volumes traversed by the particle at front-end level, 4) the increase of the particle region of influence at layout level and 5) the amplification of parasitic effects as a function of device architecture considered.

The critical charge (Qcrit) corresponds to the minimum charge disturbance needed to flip a logic level. Fig. 5 shows the drastic reduction of this charge when pushing device integration for bulk and Silicon-On-Insulator (SOI) technologies. Current technologies (28 nm and 22 nm nodes) are operating in a Qcrit regime of a few thousands of electrons, or hundreds of aC, a value well below the amount of charge deposited by a singly charged ionizing particle in silicon. Consequently, logic circuits with low node capacitances and operating under low power supply voltages will be more susceptible to suffer from soft errors than previous generations of circuits. Reduced Qcrit also leads to expand the spectrum of particles to which a circuit is sensitive. Although a very low ionizing power, atmospheric muons and low energy protons are now capable of creating upsets in the most integrated technologies.

Low energy protons (≤10 MeV) are primarily a concern for space applications, although they can also be generated by sea-level neutrons colliding silicon nuclei or by the local environment at ground level (see Section 2.1). Recent proton testsings have demonstrated their importance to SER for bulk SRAMs in 40 nm and 28 nm. In a similar way, atmospheric muons, that are the most preponderant charged particles at sea level (see Fig. 2), are also susceptible to represent a new radiation threat for deca-nanometer technologies, specially operated at ultra low voltages. The uncertainty of the terrestrial muon flux below a few hundred MeV does not yet enable an accurate estimation of their direct SER impact at ground level, even if 1000× projections have been made [34]. Moreover, when negative muons have lost their kinetic energy and stop, about 35% spontaneously decay. The remaining 65% are captured, producing in silicon unstable aluminum that can de-excite by evaporation. This additional mechanism should be a potential source of soft errors for future technologies [8].

Other important issues have been identified for bulk or SOI deca-nanometer technologies [34]: the growing importance of telluric rays (alpha particles generated from traces of radioactive contaminants in IC materials), the lesser efficiency of classical mitigation techniques, the enhanced Total Ionizing Dose (TID) due to X/gamma rays (also protons, electrons, etc). We try to summarize in the following the most important key points of these issues for current commercial bulk and SOI technologies.

- **Bulk technologies:** the evolution of the measured single-bit SRAM SER as a function of technology nodes shows that the SER per bit has peaked at the 130 nm technology node and since then is decreasing. This current reduction tendency can be explained by the dramatic reduction of the charge collection volumes due to the geometrical scaling compensating lower critical charges. At chip level, since the cells are more densely packed with scaling, the charge from a single particle is more easily shared among several cells. This reduces the amount of charge effectively collected by an individual cell. The net effect is an improved per-bit SER of scaled technologies, as observed in DRAMs, dynamic logic, SRAMs, but not for latches and combinatorial logic [34]. Finally at circuit or system-on-chip levels, SER keeps increasing with the growing amount of memories and latches and with a particular stronger SER impact on latches. The decrease of supply voltages for higher power efficiency (e.g. for cloud computing) is an aggravating factor and will constitute a grand reliability challenge.

- **SOI technologies:** the sensitive volume traversed by an ionizing particle is even further reduced with the isolation barriers, resulting in a stronger intrinsic SER resilience in SOI compared to bulk. This total isolation of device also removes the parasitic thyristor at the origin of single event latch-ups (SEL). SOI technologies are then immune to SEL by construction and this immunity is also verified for hybrid bulk devices in FDSOI 28 nm [34]. However, a stronger parasitic bipolar in SOI can degrade SER despite small critical charges and small sensitive volumes. Connecting the partially-depleted (PD)-SOI internal body to either source or ground greatly improves SER, but induces area penalty. In Fully-depleted SOI 28 nm, the bipolar gain has been measured very low (<3 in the worst case) and full benefit can be taken from the ultra-small sensitive volume, thus strongly minimizing SER. Recent results have experimentally demonstrated a 110× reduction factor in the high-energy neutron SER in FDSOI 28 nm compared to bulk 28 nm, with the lowest failure-in-time (FIT) rate ever observed for SRAMs (<10 FIT/Mbit) [34].

To conclude, Table 1 summarizes the expected SER, SEL and totalizing dose (TID) performances between CMOS bulk, FinFET and SOI technologies. This table has been compiled from references cited in [34] and offers a global overview of the performances, drawbacks and main challenges for the upcoming technologies. Certain issues for ultra-scaled SOI devices or FinFET architectures should be investigated in-depth in future studies.
6. Conclusion

Radiation effects on CMOS technologies at ground and atmospheric levels have deeply evolved in the last decade, since typically the introduction of the bulk 130 nm technology node. The geometrical scaling combined with the core voltage reduction has induced the emergence of new mechanisms (charge sharing, bipolar amplification, carrier channeling in wells) and enlarged the region of influences of particles in circuits (multi-node charge collection). All these effects have profoundly modified the radiation response of device and circuits. The latter have become more sensitive to radiation (alpha particle emitters, low energy protons, atmospheric muons). Understanding evolving error mechanisms in new device architectures and circuits (extended to new particles as muons) and the physics of soft actions (extended to new particles as muons) and the physics of soft channeling in wells) and enlarged the region of in

Table 1

Expected SER, SEL and TID performances between CMOS bulk, FinFET and SOI technologies. Adapted after [34].

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<tr>
<th>With respect to bulk CMOS</th>
<th>PD-SOI</th>
<th>Bulk FinFET</th>
<th>SOI-FinFET experimental</th>
<th>UTBB-FDSOI</th>
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<tr>
<td>Critical charge</td>
<td>0.1 fC</td>
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<td>Minimal charge to upset</td>
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<td>Sensitive volume</td>
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<td>Charge deposition and collection</td>
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<td>Paracitic bipolar</td>
<td>Significant w/o body ties &lt; 20</td>
<td>Ultra low substrate tied to body</td>
<td>Low ~ 2–8</td>
<td>Ultra low &lt; 3</td>
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<td>Charge amplification</td>
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<td>Alpha/neutron-SER</td>
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<td>New SER risk (to be evaluated)</td>
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<td>Muon-SER</td>
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<td>No data yet in literature</td>
<td>Immune by construct Mbad with narrow fins</td>
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References


Please cite this article as: Autran JL, Munteanu D, Radiation and COTS at ground level, Microelectronics Reliability (2015), http://dx.doi.org/10.1016/j.microrel.2015.06.030.