Single-Event Upsets in Microelectronics: Fundamental Physics and Issues

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Abstract

We review the current understanding of single-event upsets (SEUs) in microelectronic devices. In recent years, SEUs have been recognized as one of the key reliability concerns for both current and future technologies. We identify the major sources of SEUs that impact many commercial products: (1) alpha particles in packaging materials, (2) background radiation due to cosmic rays, and (3) thermal neutrons in certain device materials. The origins of SEUs are examined from the standpoint of the fundamental atomic and nuclear interactions between the intruding particles (alpha particles, cosmic rays, and thermal neutrons) and semiconductor materials. We analyze field funneling, which is a key mechanism of charge collection in a device struck by an ionizing particle. Next, we formulate how SEU cross sections and SEU rates are calculated and discuss how these basic quantities are related to experiments. Finally, we summarize the major SEU issues regarding modeling, bulk complementary metal oxide semiconductor technologies, and research on future, exploratory technologies.

Keywords: *microelectronics, radiation effects, semiconductors, single-event upsets (SEUs), soft error rates.*

The Nature of Single-Event Upsets

Any charged particle passing through a microelectronic device ionizes the material(s) along its path. A column of transient electron–hole pairs is created around the particle track. These induced free carriers, if left alone in a field-free host medium, will eventually recombine. However, under appropriate operating conditions in a device, recombination of these electrons and holes can be prevented by the intrinsic, strong, internal electric fields. This can generate an electrical pulse large enough to disrupt normal device operation. This disruption caused by one random intruding particle is not associated with any permanent damage to the device. The result is an error in one bit, which, however, cannot be duplicated because of its random nature. In the microelectronics industry, this phenomenon is called a single-event upset (SEU), a soft error, or a soft failure. Charged particles are not the only agents that can cause SEUs. For reasons explained later, electrically neutral subatomic particles such as neutrons are known to cause soft failures in circuits.

SEUs are complex. To understand this subject in depth, one must consider the particle origins, which involve esoteric subjects such as cosmic rays, nuclear reactions, atomic processes, and novel modes of carrier transport in deep submicrometer devices. Radiation effects induced by subatomic particles in electronic devices and circuits have been known for a long time. Yet, with few exceptions, the subject is discussed only in a limited number of research journals and is not readily accessible to a wider technical audience. In recent years, SEUs have been recognized as a key area limiting the reliability of many mainstream technologies. The general consensus is that SEUs and radiation hardening (i.e., intentional improvement in a device's ability to withstand high-radiation environments) are of growing concern to both the commercial and space-based semiconductor industries. See the article by Baumann in this issue of *MRS Bulletin* for an excellent overall view of SEU problems from a global technology standpoint. In this article, we summarize our present understanding of SEUs from the fundamental physics viewpoint. We believe that a firm understanding of the underlying physical processes is key to developing sound judgments and strategies for resolving SEU issues in current and future products.

In the following sections, we review the three known sources of SEUs; discuss the fundamental atomic, nuclear, and device physics; introduce the basic concepts of the SEU cross section and the soft error rate (SER); and, finally, summarize the status of current SEU research.

Major Sources of Single-Event Upsets

There are several known sources of SEUs that affect microelectronic devices. Alpha particles emitted from packaging materials were discovered to cause SEUs in dynamic random-access memories by May and Woods at Intel Corp. in 1979.[1] In the same year, Ziegler at IBM and Lanford at Yale University predicted that terrestrial cosmic rays could cause SEUs in commercial electronic devices.[2] Their prediction was confirmed by experimental measurements of soft failures in mainframe computers in the 1980s.[3] In the early 1980s, McNulty alerted the physics community that there were serious SEU problems for electronic components in space programs.[4] In 1995, Baumann et al. at Texas Instruments reported SEUs caused by thermal neutrons.[5] In the past few years, the international high-energy physics community discovered SEU problems in some projects,[6] where SEUs in detector electronics were found to be caused by radiation generated by high energy beams interacting with surrounding materials. Designers of recent experiments have paid special attention to SEU events in their detectors.[7]

Alpha-Particle Generation in Packaging Materials

The oldest SEU problem can be tracked to certain packaging materials used in integrated circuits (ICs). These materials contain traces of radioactive atoms that emit alpha particles (helium-4 nuclei). A notorious example is lead, which is a common soldering material used in ICs. It turns out that lead often contains polonium-210 atoms, which have a half-life of 138 days and decay as

$$^{210}\text{Po} \rightarrow {}^{206}\text{Pb} + {}^{4}\text{He}. \quad (1)$$

The alpha particle in Reaction 1 carries a kinetic energy of 5.3 MeV. When an alpha particle penetrates the materials above a device and hits a sensitive volume, it can generate an electrical pulse that can lead to an SEU in the circuit. (A 5.3-MeV alpha particle travels at a speed of 1.6×10^9 cm/s; it has a mean range of 26 μm in silicon, and 23 μm in SiO_2).

The origin of alpha-induced SEUs is well known. The mitigation of this problem relies on improvements in the packaging processes and using alpha-free materials. From a research standpoint, alpha-induced SEUs for each new technology provide a prototypical scenario for how an ionizing particle interacts with a semiconductor device. Experiments using monoenergetic alpha ions (and other heavy ions) and theoretical device simulations of ion strikes are essential to form an understanding of device sensitivity to this failure mechanism. A more detailed picture of alpha SEU processes is given in the section on "Field-Assisted Funneling Mechanism."

Background Radiation from Cosmic Rays

Of all the SEU sources discussed here, cosmic rays are by far the most important. This, however, does not necessarily imply that, for a given technology, the SEU rate from cosmic rays is larger than that from other sources. The underlying reasons are complex and subtle and, until recently, the situation with cosmic rays has not been fully appreciated. Commercial electronics are affected by cosmic-ray particles, which carry kinetic energies spanning the range from milli- to gigaelectronvolts. In view of this wide energy range, designing effective radiation shielding valid for all possible applications and in all environments is not a viable solution. In addition, cosmic-ray fluxes are subject to large changes due to constant fluctuations of atmospheric conditions, the earth's magnetic field, solar winds, solar activities, and even supernova explosions. All of these factors are clearly beyond human control. Invoking global technological reasons, Baumann's article in this issue predicts that cosmic ray-induced SEUs will continue to be an important reliability issue for future products.

A detailed discussion of the origin and physics of cosmic rays is beyond the scope of this article (see, e.g., Reference 8 for further details and Reference 9 for a lively and up-to-date account of cosmic-ray research geared toward nonspecialists). The primary cosmic rays in outer space come from two sources: (1) intragalactic particles entering the solar system and hitting the earth's atmosphere at typically ultrarelativistic speeds; and (2) solar cosmic rays from solar winds. These primary cosmic rays are composed of approximately 98% atomic nuclei and 2% electrons. Of these atomic nuclei, about 90% are protons and 9% are alpha particles, with the balance consisting of lithium, boron, carbon, nitrogen, oxygen, and heavier nuclei. Very few of these high-energy particles reach the surface of the earth. The particles that do hit earth-based commercial electronics are the secondary cosmic-ray particles from the aptly named "extensive air showers," or EAS. EAS are the nuclear debris resulting from various interactions between the primary cosmic rays and the atmosphere.

The earth's magnetic field acts as an effective shield, and a charged primary cosmic-ray particle is constantly deflected from its path. As it penetrates into the atmosphere, the primary cosmic-ray particle collides with air molecules and loses energy. These collisions produce ionized molecules and secondary subatomic particles by nuclear spallation reactions. During a spallation event, a violent process that liberates the nuclear binding energies of the colliding nuclei, many secondary particles are created—typically protons, neutrons, pions, residual nuclei, and gamma rays. The first generation of secondary particles propagates down into the atmosphere and cascades into subsequent generations of secondary particles, producing a particle shower. Depending on the energy of the initial primary cosmic particle, the radius of the circular area covered by this shower can be as large as several hundred meters.

Figure 1 shows the typical spectra of terrestrial cosmic-ray particles.[3] Energy differential fluxes are plotted against particle kinetic energy. The upper dotted curve, computed using a Boeing–NASA model,[10] is the neutron flux spectrum at 40,000 ft (~12 km). Below 100 MeV, the sea level spectra are dominated by neutrons and muons, with small contributions from protons and pions. At energies above 100 MeV, muons dominate the spectra. As one goes from sea level to higher altitudes, the cosmic flux increases and then reaches a maximum at about 15 km—the Pfotzer point—beyond which the flux decreases.

From the standpoint of SEUs, neutrons are the most important part of the terrestrial cosmic rays. Details of the terrestrial neutron spectra are discussed in the article by Goldhagen in this issue of *MRS Bulletin.* Cosmic protons and pions play a relatively minor role, except at high altitudes. When a neutron penetrates a chip, it occasionally collides with an elemental nucleus, for example, a silicon nucleus in a device region, an oxygen nucleus in the oxide layer, or a copper nucleus in the metal layer. This neutron–nucleus event initiates a local spallation reaction. Some of these fragments may hit a sensitive device region and cause an SEU. In essence this neutron–nucleus collision is identical to the initial cosmic-particle cascade in the upper atmosphere, except that the neutron reaction occurs locally in a device and takes place on a much reduced energy scale.

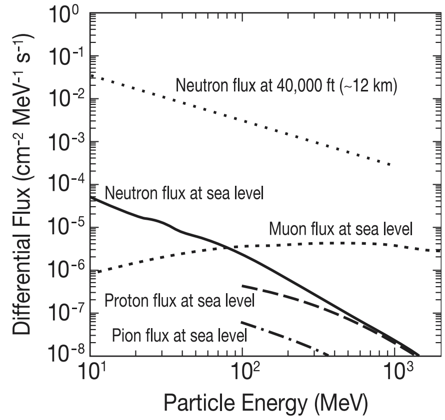

Figure 1. Spectra of terrestrial cosmic rays: energy differential fluxes plotted against particle kinetic energy.

Despite the significant muon flux shown in Figure 1, muons are much less effective than neutrons in causing SEUs. Unlike neutrons, which interact with a nucleus through the strong nuclear force, a muon interacts with semiconductor materials through the weaker electromagnetic force. In general, the ionization energy deposited by a muon is too small to induce an SEU.[11]

Thermal Neutrons

For several recent technologies, thermal neutrons were discovered to be a major SEU issue. Thermal neutrons (n_{th}) are slow neutrons with kinetic energies in the millielectronvolt range. Their energy distribution is strongly dependent on the environment. Borophosphosilicate glass (BPSG), often used as an insulator layer adjacent to a device, is heavily doped with boron. Natural boron contains 80% ^{11}B and 20% ^{10}B. When a thermal neutron (n_{th}) passes through BPSG, the following capture reactions can occur:

$$n_{th} + {}^{10}B \rightarrow {}^{4}He\ (1.47\ MeV) + {}^{7}Li^{*}\ (0.84\ MeV). \quad (2a)$$

$$n_{th} + {}^{10}B \rightarrow {}^{4}He\ (1.78\ MeV) + {}^{7}Li\ (1.02\ MeV). \quad (2b)$$

The dominant decay mode (Reaction 2a), with a branching ratio (i.e., probability of occurrence) of 94%, yields a 1.47-MeV alpha particle and a 0.84-MeV ^{7}Li nucleus. This ^{7}Li nucleus is in an excited state (shown as ^{7}Li*) and eventually decays to the ground state by emitting a 0.48-MeV gamma ray. The second decay mode (Reaction 2b), with a branching ratio of 6%, gives a 1.78-MeV alpha particle and a 1.02-MeV ^{7}Li nucleus. This reaction is important because the n_{th}-^{10}B capture cross section is huge. For example, the capture cross section for a 25-meV neutron on ^{10}B is 3838×10^{-24} cm^2. This cross section is energy-dependent; it decreases with increasing neutron energy according to a $1/E^{1/2}$ law, where E is the neutron kinetic energy (from millielectronvolts up to about 0.5 MeV). The cross section of a reaction is a measure of the strength of the interacting particles, that is, a large cross section implies a strong interaction between the particles, while a small cross section implies a weak interaction between them. For comparison, an energetic 100-MeV neutron on Si has a reaction cross section (associated with inelastic scatterings) of about 300×10^{-27} cm^2, which is about four orders of magnitude smaller than the thermal neutron capture cross section on ^{10}B.

Furthermore, in Reactions 2a and 2b, because the incident neutron is slow, the emitted particles—alpha and lithium nuclei—are essentially emitted in opposite directions due to momentum conservation. Therefore, it is unlikely that these nuclei are emitted parallel to the underlying device. Hence, once the thermal neutron reaction takes place, the probability that one of the emitted nuclei will hit a sensitive device region is high.

Where do thermal neutrons come from? To answer this question, one needs to consider how the thermal neutron was discovered. Enrico Fermi and his group in Rome discovered thermal neutrons in 1934. When they put paraffin (intended as a shield) between a neutron source and a Geiger counter, an unexpectedly high neutron count was found. After ruling out the possibility of detector malfunction, the puzzle was solved by Fermi, who recognized that hydrogen present in the paraffin was an effective moderator that slowed megaelectronvolt neutrons down to form thermal neutrons. For a vivid firsthand account of this discovery (which subsequently led to other events of historical significance for the Manhattan Project), refer to the Fermi Memorial Lecture by E. Segre.[12]

Physical Processes Leading to Single-Event Upsets

Atomic Processes: Radiation Energy Due to Direct Ionization

As a charged particle penetrates a material, it slows down and loses kinetic energy at the expense of the excitation and ionization of the atoms surrounding the particle path. This form of radiation energy is characterized by the linear energy transfer (LET), or stopping power, that is, the energy loss per unit path length. In silicon, it takes an average energy of 3.6 eV to create an electron–hole pair. Hence an LET of 1 MeV/μm is associated with 2.78×10^5 electron–hole pairs per micron; that is, 44.5 fC of electrons, and 44.5 fC of holes per micron.

LET of Cosmic-Ray Particles. Figure 2 shows the LETs of charged particles from terrestrial cosmic rays in silicon-28: proton, charged pion, muon, and electron, plotted versus particle energy, up to 1 GeV.

At incident energies above 1 MeV, the ionization energy deposited by a proton is usually too small to cause SEUs. High-energy protons cause SEUs through the highly ionizing secondary fragments they produce when they collide with silicon nuclei. Between 1 MeV and 1 GeV, the pion and muon LET curves are below the proton curve. Hence, in general, pions and muons are less ionizing than protons. Like protons, high-energy pions induce SEUs mainly by nuclear spallation reactions. Muons, however, do not interact with nuclei by the strong nuclear force. In most terrestrial applications, muons do not pose serious SEU problems. There are rare events due to the formation of pionic and muonic atoms. A low-energy negative pion or negative muon (in the kiloelectronvolt range) can replace an orbiting electron to form a pionic atom or a muonic atom, respectively. This atom is unstable, and the pion or muon eventually collapses into the nucleus, which then disintegrates, emitting heavily ionizing fragments. However, Reference 11 shows that these exotic cases are too rare to be of concern in most applications.

LET of Spallation Fragments. In Figure 3, the LETs of four ions are plotted for comparison: hydrogen (proton), helium-4, beryllium-9, and oxygen-16. These ions, as well as others, are produced as spallation products when a high-energy neutron, proton, or pion collides with a nucleus in a semiconductor material. The LET varies approximately as Z^2/v^2, where Z is the ion charge and v is the ion velocity. Hence, the LET of a spallation fragment with a large charge is usually larger than a fragment with a smaller charge at the same energy. A spallation reaction typically results in the production of a residual nucleus (lighter than the initial nucleus); this nuclear debris carries a large charge, but moves slowly in the host material. Hence, the residual nucleus usually deposits the largest ionization energy, compared with the lighter secondary fragments produced in the same collision event.

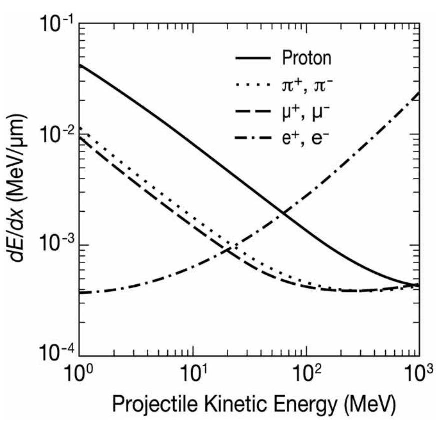

Figure 2. Linear energy transfer (dE/dx) of cosmic-ray particles (protons, charged pions, muons, and electrons) in silicon-28.

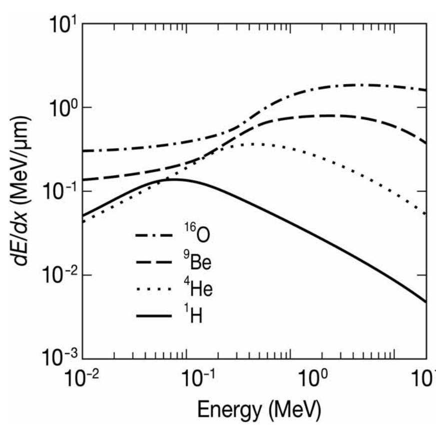

Figure 3. Linear energy transfer of typical spallation fragments in silicon: hydrogen, helium-4, beryllium-9, and oxygen-16.

Field-Assisted Funneling Mechanism

From a device physics standpoint, a key mechanism that leads to SEUs is the field-assisted funneling process, first discussed in detail in a 1983 paper by Hsieh, Murley, and O'Brien at IBM.[13] Figure 4 shows the cross-sectional view of a typical bulk metal-oxide-semiconductor device. When a charged particle such as an alpha particle hits the device, electron–hole pairs are generated around the projectile's path. These electrons and holes in turn perturb the electric field in the device. As a result, the equipotential surfaces of the electric field are distorted from their equilibrium configuration in such a way that they wrap around the particle track in the shape of a funnel. In Figure 4, the projection of such an equipotential surface onto the device cross section is depicted as a dotted equipotential line. At any point on the equipotential line, the electric-field vector is always perpendicular to the line. Hence, the electric force will always push negative electrons in one direction and positive holes in the opposite direction. This further separates the electrons and holes, and recombination is delayed or prevented. Eventually, excess charge of one type is collected as an electrical pulse in the drain region (which is often connected to a circuit node), while the excess charge of the opposite polarity is swept into the substrate. If this collected charge exceeds a threshold value known as the critical charge, the state of the cell can be changed, and an SEU is said to have occurred. The critical charge is an important device parameter and is closely related to SEU sensitivity.

When a neutron, being electrically neutral, hits a device, it does not deposit any energy by direct ionization. However, it interacts with a silicon nucleus by means of a spallation reaction, resulting in the break-up of the silicon nucleus and production of charged secondary particles. These secondary particles will ionize the device and cause an SEU in a similar manner as an alpha particle. Neutron–nucleus collisions are random events. For a given device/circuit configuration, the probability of a neutron–nucleus collision is computed from certain nuclear cross sections. The energy and angular distributions of the spallation fragments are critical inputs for such SEU simulations; they must be either computed from appropriate nuclear models,[11,14] or obtained from nuclear experiments.[15] The article by Bernstein in this issue of *MRS Bulletin* addresses the subject of how the electrical pulse generated in a radiation event propagates in a circuit and causes SEUs.

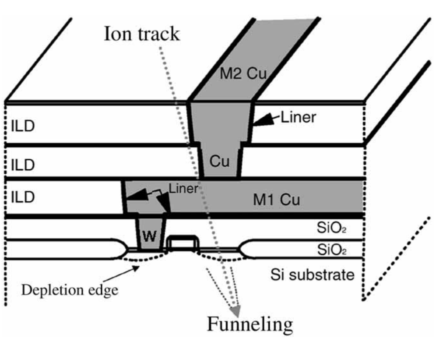

Figure 4. Schematic illustration of the field-assisted funneling mechanism in a metal-oxide-semiconductor device hit by an ion. ILD is interlayer dielectric. M1 and M2 are metal levels produced by separate processes during fabrication.

Nuclear Processes Relevant for SEUs

Certain hadron–nucleus reactions are important for SEU studies.[11,14–16] Hadrons are a class of subatomic particles that interact with nuclei through their strong nuclear force. These include protons, neutrons, and pions, which are also components of cosmic rays. The conclusion that spallation reactions cause SEUs is based on the following experimental observations. First, neutrons at all energies are known to induce SEUs in circuits. Since neutrons do not cause electronic ionization in devices, neutron-induced SEUs must be caused by processes that are of non-electromagnetic origin. (Strictly speaking, neutrons carry magnetic moments, and as such, interact with electrons. However, these interactions, in general, do not cause effects strong enough to account for the observed SEUs.) Second, proton-induced SEU cross sections of chips from many technologies have a simple, universal shape. Plotted against particle energy, the SEU cross section is near zero below an "energy threshold," rises rapidly with increasing energy, and finally levels off at high energies above 100 MeV. For technologies with large critical charge (e.g., >100 fC), the energy barrier is high, indicating that the energy deposited from direct-ionization processes is insufficient to cause SEUs. Because the proton LET is small at high energies (which implies small energy deposition from direct ionization), one comes to the important conclusion that the observed SEU is caused mainly by the secondary fragments produced from proton–nucleus spallations. Various aspects of nuclear spallations relevant for SEUs are discussed in detail in References 11, 14, 15, and 16. A critique on modeling spallation reactions is given in Reference 14 in the context of a cascade-statistical model for nuclear reactions.

Characterization of SEU Sensitivity

There are two complementary quantities one uses to specify SEU sensitivity: (1) the SEU cross section, and (2) the SER. The SEU cross section is an intrinsic parameter of a chip that characterizes its SEU response to a particle species. It is usually measured in an accelerator test using a monoenergetic beam. The SER, on the other hand, is a measure of the chip's response to a particular radiation environment. It is measured by both accelerator and life tests. Whereas the SEU cross section at a given energy is a fixed number, the SER changes with the environment. For example, the SER of the chip on top of a mountain can increase by more than an order of magnitude for the same chip at sea level, due to an increase in the background neutron flux.

SEU Cross Section

The SEU cross section of a chip due to a particle (neutron, proton, pion, or heavy ion) is a fundamental quantity that can be directly measured. Consider a test sample, consisting of a number of identical chips, that is irradiated by a uniform, monoenergetic beam of particles. For simplicity, we assume that the incident particles impinge on the sample in a normal direction, as is the usual case in an accelerator experiment. We further assume that the intensity of the particle beam is sufficiently small that only a single bit fails at a time. The SEU cross section is defined as

$$\sigma_{\mathrm{SEU}}(E) = (dN_{\mathrm{f}}/dt)/\phi_0, \tag{3}$$

where E is the energy of the incident particles, dN_{f}/dt is the failure rate (failures/s), and ϕ_0 is the particle flux (number of particles/cm^2 s). The SEU cross section is often normalized to units of cm^2/bit. Note that dN_{f}/dt is measured directly in an experiment and ϕ_0 is controlled by setting the incident beam flux. In general, the SEU cross section depends on the particle species and energy. SEU cross sections are sensitive to device/circuit parameters such as critical charge and vary with operating conditions such as the applied voltage.

One of the objectives of modeling is to understand how the underlying particle interactions, basic device parameters, and operating conditions affect the SEU cross section, thus allowing one to make SEU projections for future products and technologies.

Calculations of SER and SEU Cross Section

To compute the SER of a chip in a radiation environment, one needs the energy distribution of particles that cause SEUs and also the SEU cross section as a function of energy. The SER is computed as

$$\frac{dF}{dt} = \int_{E_{\min}}^{E_{\max}} \frac{d\phi(E)}{dE} \sigma_{\mathrm{SEU}}(E)\, dE, \tag{4}$$

where F is the number of failures per bit, t is time, E is the particle energy in megaelectronvolts; $d\phi(E)/dE$ is the energy differential particle flux (number of particles/MeV cm^2 s), $E_{\min}$ and $E_{\max}$ are the lower and upper bounds of the energy spectrum, and $\sigma_{\mathrm{SEU}}(E)$ is the SEU cross section. The SER is often quoted in units of FIT/bit, where 1 FIT (failure in time) is equal to 1 failure/10^9 operating hours.

Theoretically, the SEU cross section can be computed by the generic formula

$$\sigma_{\mathrm{SEU}}(E) = A\rho_{\mathrm{atom}}\sigma_{\mathrm{nucl}}(E)D_{\mathrm{eff}}\int_{Q_{\mathrm{crit}}}^{\infty} F_{\mathrm{cc}}(Q;E)\, dQ, \tag{5}$$

where A is the surface area per bit of the sample (cm^2), ρ_{atom} is the number density of atoms in the chip (atoms/cm^3), $\sigma_{\mathrm{nucl}}(E)$ is the total cross section associated with the SEU-causing nuclear processes (cm^2), D_{eff} is a length that characterizes the depth of the chip to which the spallation fragments penetrate to cause SEU, Q_{crit} is the critical charge, Q is the charge collected (fC), and F_{cc} is a probability density of charge collection (fC^{-1}). Note that $F_{\mathrm{cc}}(Q;E)\,dQ$ is the probability, during a nuclear collision event, that the charge collected is between $Q - dQ/2$ and $Q + dQ/2$.

From Equations 4 and 5, it is clear that realistic calculations of failure rates require three inputs: (1) particle flux associated with the environment, (2) device/circuit parameters, and (3) probabilities of various nuclear processes related to SEUs. The probability density function, F_{cc}, in Equation 5 plays a central role in SEU modeling. For the construction of F_{cc}, it is essential to use appropriate device models of charge generation and collection and accurate nuclear models that simulate the distributions of spallation fragments produced from hadron–nucleus collisions.

Summary of Current Issues

SEU Sources

Of the three major SEU sources, cosmic rays will continue to be an important reliability concern in the future. Accurate energy-differential spectra of cosmic particles are crucial for realistic SEU rate calculations.

For most commercial electronics (except those used in space programs), terrestrial cosmic neutrons are the most important component. As the critical charge in new devices decreases, the energy threshold for neutron-induced SEUs decreases. For example, in the technologies of the early 1990s, neutrons below 50 MeV caused negligible soft failures, but in current technologies, neutrons with energies down to 20 MeV are known to cause failures. The energy threshold will continue to decrease to below 10 MeV; this is to be expected if one takes note of the fact that the alpha production threshold in neutron–silicon reactions is around 5 MeV. New and refined measurements of environmental neutron flux, on the ground, at high altitudes, and at energies below 50 MeV, are required in order to benchmark SERs for future products. Furthermore, at high altitudes, proton and pion fluxes are considerably larger than at sea level, and their contributions to the total SER can no longer be ignored.

Device Modeling Issues

For bulk devices, the general consensus is that field-assisted funneling is the major charge-collection mechanism. In SEU modeling, this mechanism is often incorporated as a funneling length parameter that is estimated from device simulations and calibrated with experimental data.

In some new exploratory devices, because the Si volume available for charge collection is negligibly small, funneling is not expected to play a major role. Compared with bulk devices manufactured by comparable technologies, these devices are less susceptible to SEUs. However, experiments indicate that these new devices are not completely immune to SEUs, presumably due to certain amplified parasitic bipolar effects.[17] New charge-collection mechanisms are obviously at work. At present, a complete analysis of SEU processes in these new devices, consistent with all experimental observations, remains to be formulated.

Nuclear Data and Experiments

Simulations of nuclear spallations and the use of certain nuclear data provide crucial inputs for SEU analyses. In the mid-1980s, IBM developed a comprehensive system of simulation models for SEU analyses and product design. These models are based on detailed Monte Carlo simulations of spallation reactions and device charge-collection processes.[11,14,18] In the last 10 years, other major companies (e.g., Fujitsu, Hitachi, and NEC) have reported comprehensive SEU simulations using similar methodologies. Reference 15 gives a review of data from nucleon-induced reactions on light elements; these data are particularly important for SEU work. The article by Blomgren et al. in this issue of *MRS Bulletin* discusses the relevance of new neutron data and new experimental projects on recoil measurements that are motivated by SEU studies.

SEU Cross Sections

Experimentally, heavy-ion SEU cross sections plotted against LET result in a simple curve that is well fitted to a Weibull distribution. For a given device, to a first order, this curve depends only on LET and is independent of the ion species. This strongly suggests that the energy deposited (or equivalently, the charge deposited) is a key parameter. This experimental observation applies to many generations of bulk complementary metal oxide semiconductor technologies. Recent results from heavy-ion experiments strongly indicate that this feature may also apply to new exploratory devices. As an example, Figure 5 shows heavy ion SEU cross section versus effective surface LET.[19] Here, the effective surface LET is the LET of the ion on the Si surface after the energy loss through the materials on top of the device has been accounted for. Using nuclear model simulations and experimental heavy-ion SEU cross sections for a group of bulk devices, the authors in Reference 6 have simulated proton SEU cross sections that are shown to compare well with experiments. This establishes a direct correlation between proton and heavy-ion SEU cross sections. In situations where experimental proton and neutron SEU cross sections are not available, this provides a practical means for constructing the data. Work to establish similar correlations between proton and heavy-ion SEU cross sections for exploratory devices in new technologies is in progress.

Concluding Remarks

We have reviewed our current understanding of single-event upsets (SEUs) from the standpoint of fundamental physics. Technology trends—lower applied voltage, decreased intrinsic capacitance associated with scaling, and so on—all lead to much lower critical charge in devices. The advantages gained by smaller charge-collection volumes are offset by the increase in device density per chip. The combination of all of these technological factors results in a gradual rise in SEU sensitivity (on the basis of soft failures per

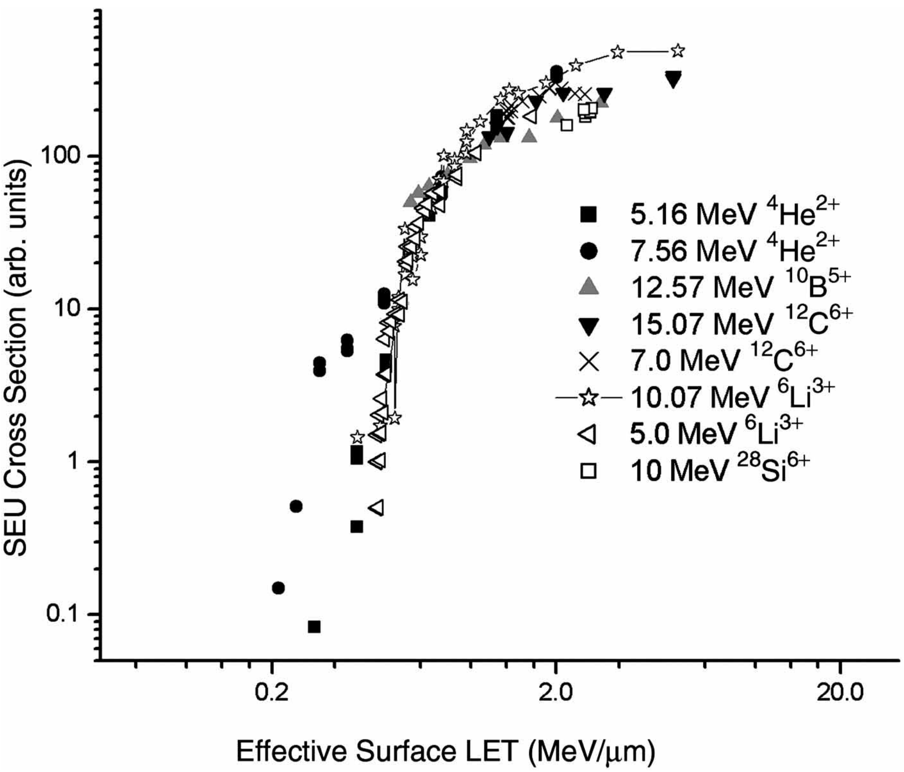

Figure 5. Heavy-ion single-event upset (SEU) cross section versus effective surface linear energy transfer (LET).[19] (Courtesy of T.H. Zabel.)

chip) from generation to generation. This trend is already observed in bulk complementary metal oxide semiconductor technologies. Some of our major challenges in the future will involve the search for options offered by new advanced technologies. For these new technology advances, SEU reliability will continue to be a key issue that will demand considerable attention.

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