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Single Event Effect Immunity for Life Critical Applications

June 2012

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Overview

Sophisticated electronics have found their way into a number of medical applications, from implantable devices to diagnostic and therapy equipment. These devices can be exposed to high levels of ionizing radiation, whether it is an implantable device in the patient traveling in commercial aircraft flying at high altitude or the control equipment of diagnostic equipment exposed to the scatter from radiation sources. This ionizing radiation can alter the bit states of any embedded memory device, with the likelihood of upset increasing as process geometries shrink.

While the impact of this radiation on memory circuits is well known, the fact that FPGAs and customizable system-on-chip (cSoC) devices are immune to radiation is not widely known.

Given that the lives of many patients depend upon the reliable operation of these devices, designers of medical devices need to understand these risks as well which technologies offer immunity to the effects of ionizing radiation on their programming.

Single Event Effects

Generally, any effect induced by a single radiation event on an electronic circuit (as opposed to effects due to collective dosage), whether transient or damaging, are collectively referred to as single event effects (SEEs). There are three subclasses of SEEs that are the focus of this paper: single event upsets (SEUs), single event functional interrupt (SEFIs), and single event transients (SETs). See *Understanding Single Event Effects (SEEs) in FPGAs* for more details.

When charged particles strike the silicon substrate of an IC, they leave an ionization trail (Figure 1). Similarly, when a high-energy particle, for example a neutron, strikes the substrate, it collides with atoms in the substrate, liberating a shower of charged particles which then leave an ionization trail. For example, a neutron striking a silicon atom can release energy through elastic and inelastic scattering events or via spallation events that release magnesium and aluminum ions along with alpha particles and protons.

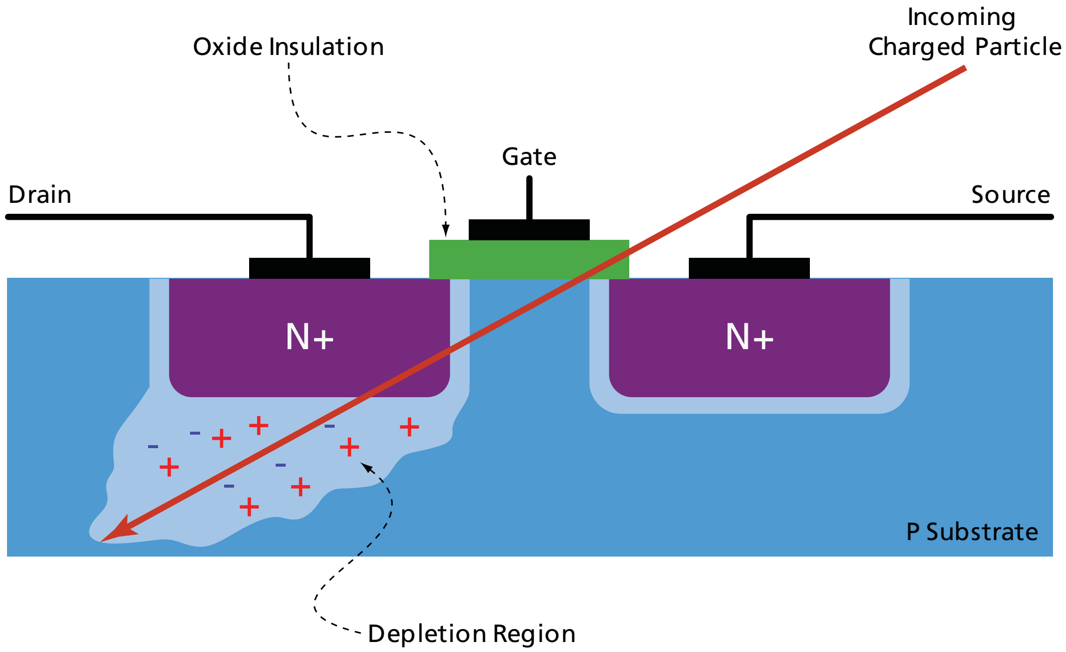

Figure 1: **Impact of a High-Energy Particle**

When a high-energy particle or ion impacts at the depletion region of a N-P junction, charges can collect in the region, creating voltage and current transients. The resulting charge can be sufficient to overpower the junction and cause a change in state (bit flip) of the memory element (SRAM cell, register, latch, or flip-flop). This change in state is referred to as a single event upset (SEU). Because the effect is temporary, these errors are often referred as being soft—only the data stored in the element is corrupted.

SEUs are of particular concern in SRAM-based devices and FPGAs. The configuration memory of these devices are constructed out of SRAM cells and are consequently susceptible to SEUs, possibly resulting in changes to FPGA functions. In contrast, the configuration of antifuse and flash-based FPGAs is SEU-immune.

Sources of Ionizing Radiation

Due to the wide application of medical technology, from wearable and implantable devices to radiotherapy equipment, medical devices can be exposed to a number of potential sources of ionizing radiation:

- Galactic cosmic rays
- Radiation sources used by diagnostic and therapeutic equipment
- Device packaging materials
- Silicon substrate dopants

Galactic Cosmic Rays

The most prevalent source of ionizing radiation is galactic cosmic rays (GCR). This radiation is comprised of high-energy particles, overwhelmingly protons, and impacts the Earth’s atmosphere constantly. These particles, originating in space, have sufficient energy to liberate nuclei when they collide with molecules in the Earth’s atmosphere. The result of this collision is referred to as an air shower, where a wide range (and high number) of particles is generated. The primary spallation products of concern to designers are neutrons and protons (in addition to remanent cosmic rays). The resulting particles from these rays range in energy between 1 and 10 MeV.

The flux of cosmic rays impacting the Earth’s atmosphere is modulated by both the solar wind and the Earth’s magnetic field. As a result, the greatest modulation occurs at the equator and when the solar wind is most active (when solar flare activity is high). The flux resulting from the air shower is modulated by the density of the atmosphere (expressed as depth). Combining all of these factors results in the particle flux being a function of latitude, longitude, altitude and solar activity, with the greatest flux occurring at high altitudes over the poles during quiet periods of solar activity. As a result, an observer in an aircraft flying at 40,000 feet over the poles during a period of moderate solar activity will experience more than 500 times the neutron flux as a terrestrial observer in New York City.

Medical Radiation Sources

Radiation sources are used widely in medicine, whether to diagnose or treat disease. These uses are general referred to as radiotherapy. Typically these machines use a linear particle accelerator (LINAC) to generate the needed X-ray beam to treat a tumor, for example. In a LINAC designed for radiotherapy, the accelerator generates a beam of high-energy electrons aimed at a high-density target, typically tungsten. The resulting collisions generate the X-rays needed for treating the patient.

With respect to device upsets, it is not the generated X-rays that are of concern, but rather the by-products generated when the electrons impact the target. In higher energy LINACs, a significant flux of fast neutrons (energies at or above 1 MeV) can be generated. In addition to the fast neutrons generated in line with the target of the therapeutic X-ray beam, the fast neutrons scattered in other directions and attenuated by the device shielding, walls, etc., create a background flux of thermal neutrons (energies around 0.025 eV). One study places the thermal flux at the entrance to a radiotherapy treatment area on the order of 1 mSv/h—equivalent to the exposure received during 13 flights between New York and Tokyo every hour.

A study performed by Wilkinson, et al., measured the upset rate for SRAMs exposed to the off-axis scatter from a medial LINAC operating at 18 MeV. By correlating their test data with NIST results for the same device, the authors concluded that the thermal neutron flux during treatment near the beam was 72×10^6 higher than the natural thermal neutron background flux at sea level.

Packaging

Additional radiation sources can be found in the packaging itself. Packaging materials used for integrated circuits contain trace amounts of uranium and thorium. These elements naturally emit alpha particles as they decay. Although alpha particles that result from decay have low penetration depth—a few centimeters of air can act as sufficient shielding—the proximity of packaging material to the silicon substrate make them an issue for electronic circuits.

Silicon Substrate Dopants

Another source of ionizing radiation is the element boron used in polysilicon doping, substrate doping, or borophospho-silicate glass (BPSG) in large amounts. When one of the commonly occurring boron isotopes, ^{10}B, (about 20% of total boron in nature) is struck by low-energy (thermal) neutrons, a lithium ion and an alpha particle are created in a process referred to as neutron capture:

$$n + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Li} + \alpha$$

This spectrum can be significant given the amount of boron present in substrates plus the number of thermal neutrons present during radiotherapy sessions. Because ^{10}B sources are in the device itself, no amount of outside shielding can protect against the resulting alpha particles.

For more details on the sources of ionizing radiation and its impact, see *Understanding Single Event Effects (SEEs) in FPGAs*.

Assessing the Risks

Looking at the two classes of medical devices, radiotherapy equipment and implantable medical devices, assessing the exact risk of SEEs is difficult. This paper examines the environment for each class of device and discusses what evidence of risk exists.

Implantable Devices

The two most common implantable devices are pacemakers and implantable cardioverter defibrillators (ICDs). Pacemakers are used to control abnormal heart rhythms while ICDs are used to prevent sudden death from cardiac arrest due to tachycardia or fibrillation. Due to the complexity of ICDs, these devices are more at risk.

Traditionally, the industry has focused solely on total ionizing dose (TID) effects on implantable electronics. From the perspective of TID, the amount of ionizing radiation experienced by the patient due to cosmic rays can be ignored. The focus then turned to the dosage received by a patient undergoing radiotherapy.

But in 1998, Bradley and Normand delivered the first comprehensive report on the incident of SEUs in implantable devices, showing an upset rate of 9.3×10^{-12} upsets/bit-hr based on 22 upsets experienced over a total of 284,672 device-days. Although the report lists various radiotherapy treatments that could possibly induce SEUs, this report downplays the prospect of SEU as the result of neutron scatter during radiotherapy (no upset testing was conducted in a therapeutic environment). Since 1998, process geometries have shrunk, increasing the susceptibility. to upset as well as the awareness of the high thermal neutron flux in radiotherapy environment.

Since this first report, the susceptibility of implantable devices to the effects of cosmic rays has been clearly demonstrated. In 2005, Canadian-based St. Jude Medical issued an advisory to doctors, warning that SEUs to the memory of its implantable cardiac defibrillators could cause excessive drain on the unit's battery. Other manufactures have also recognized this risk. In the Boston Scientific white paper, *Therapeutic Radiation and Implantable Pacemakers and Defibrillators*, the authors specifically warn:

> "Therapeutic radiation, including scatter particles, can have a temporary negative effect on the implanted device's electrical components such as the microprocessor or memory, resulting in temporary alteration of device function."

The white paper further lists a number of potential device errors that can result from radiation exposure (these include both SEE and TID effects).

Table 1: **Potential Temporary or Permanent Device Behaviors Due to Radiation Exposure (after Boston Scientific)**

CDs/CRT-Ds	Pacemakers/CRT-Ps	Potential Device Behaviors (Temporary or Permanent)
✓	✓	Altered device status (e.g., premature elective replacement indicator)
✓	✓	Altered pacing outputs (e.g., decreased pacing amplitude)
✓	✓	Inhibition of pacing—pacing therapy not provided when needed
✓		Altered tachyarrhythmia outputs (e.g., shock energy)
✓		Inhibition of tachyarrhythmia therapy—shock therapy not provided when needed
✓		Inappropriate shocks—shock therapy provided when not needed
✓	✓	Complete loss of device function
✓		Reversion to safety mode
	✓	Reversion to reset mode
✓		Loss of remote monitoring with the patient management system

Furthermore, the white paper states that given the variability in devices and treatments, "... it is not possible to specify a *safe* radiation dosage or guarantee proper device function following exposure to ionizing radiation."

Radiotherapy Equipment

The second class of medical equipment of concern with respect to SEE is radiotherapy equipment. As stated earlier, this class of equipment typically uses a LINAC to generate the needed beam. The resulting scatter products not only effect any implantable devices within a patient, they can also impact the control electronics within the equipment. While the electronics are not in the direct path of the X-ray beam or the high-energy neutrons (minimizing the concern of TID effects), the control electronics are exposed to the thermal neutron flux resulting from particle scattering. As shown by Wilkinson, et al, this flux is significant.

In addition to the local thermal neutron flux, the control electronics are still exposed to the high-energy neutron flux resulting from cosmic rays. While therapy areas are shielded, this shielding is only moderately effective against high-energy neutrons. Per JESD89A:

> "... it was found that two 15-cm (6-inch) slabs [of concrete] (plus associated roofing, ceiling, and flooring material, ductwork, etc. in an industrial building) reduced the high-energy portion (E > 10 MeV) of the neutron spectrum by a factor of 2.3, while the total neutron flux was reduced by a factor of only

> 1.6. As they penetrate the concrete, low-energy neutrons are scattered, thermalized, and absorbed, but the high-energy neutrons are attenuated by interactions which cause the nuclei in the shielding to emit neutrons with energies in the MeV range, regenerating the low-energy portion of the neutron spectrum."

Again per JESD89A, even the use of lead shielding can have unexpected results: "each incident high-energy neutron can liberate several neutrons with energies ~1 MeV, sometimes creating an increase of a factor of 2 or more in that region of the spectrum."

Combining all sources of neutrons, both high-energy and thermal, any electronics within radiotherapy equipment are exposed to significant sources of ionizing radiation, increasing the likelihood of an SEE. Any upset within the control electronics could result in an accidental exposure to a patient or an overdose—both with potential life-threatening consequences.

Estimating Potential FIT Rates for SRAM-Based Devices

Determining potential failures-in-time (FIT[1]) rates for a given SRAM-based FPGA exposed to atmospheric neutrons is fairly straightforward. The first step is to determine the relative neutron flux rate for the worst-case conditions (JESD89A references neutron flux relative to New York City). The relative flux rate can be derived via the equations found in Annex A of JESD89A or determined via a web-based calculator based on the standard located at www.seutest.com/cgi-bin/FluxCalculator.cgi.

In the case of radiotherapy equipment and implantable medical devices, it is the thermal neutron flux during radiotherapy that is of greater concern. Unfortunately, SRAM-based FPGAs are typically only tested using the atmospheric neutron energy spectrum (which Wilkerson, et al. have shown to drastically differ from the neutron energy spectrum found in radiotherapy treatment areas). In other words, the upset rates for SRAM-based FPGAs in high thermal neutron flux environments have not been studied.

In testing performed on a large capacity SRAM, Wilkinson, et al. found that when the device was placed approximately 50 cm off axis from an 18 MeV LINAC beam, 89 upsets were recorded during 10 minutes of testing. Unfortunately, no details of the device’s capacity or process technology were provided, making any attempt to estimate a potential FIT rate for an SRAM-based FPGA impossible.

Clearly more study is needed. As noted in a 2009 survey on the effects radiotherapy on implantable devices conducted by Hudson, et al.:

> "More in-depth studies need to be conducted on the effect of radiation on pacemakers and ICDs. When considering potential damage that may be incurred, it is important to consider all aspects of radiation therapy treatment, not just accumulated dose. These include the effect of backscatter, dose rate, fractionation and potential EMI interference with new technologies such as IMRT and respiratory gating."

Bottom line, the exact risk of using SRAM-based FPGAs in these applications is unknown, but demonstrably non-zero. In contrast to SRAM-based FPGAs, antifuse and flash-based FPGAs are immune to configuration upset, whether exposed to atmospheric or thermal neutrons.

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[1] 1 FIT = 1 failure/10^9 hours

Mitigation Only Masks the Problem

Configuration Memory Mitigation

Because of the growing awareness of SEEs, manufactures of SRAM-based FPGAs recommend various mitigation techniques, ranging from the simplistic to the more complex. The simplest method is to reconfigure the SRAM-based FPGA at regular intervals, clearing any SEUs that have accumulated. However, the time scale for reconfiguration is on the order of hundreds of milliseconds, during which, the function hosted in the FPGA is unavailable. This downtime is not acceptable in critical medical applications such as implantable devices or radiotherapy equipment.

With more recent generations of SRAM-based devices, there is a built-in error detection scheme in the configuration engine. Using a configuration memory readback feature, the CRC for each configuration frame is calculated and compared to a golden CRC. If a mismatch is detected, then an SEU has occurred and the application can reconfigure the entire FPGA. Alternately, the application can attempt to correct the error and rewrite the frame in background.

Despite any correction, the errors still propagate—only the time before they are corrected is reduced when compared to periodic whole-device reconfiguration. Moreover, the detection time is still on the order of milliseconds, equating to millions of clock cycles before an upset can be corrected—certainly enough time for an error to propagate through even the most complex systems.

For more details on SEU mitigation techniques, see *Understanding Single Event Effects (SEEs) in FPGAs*.

Mitigation Does Not Equal Immunity

Regardless of the methodology, mitigation is used to correct errors after the fact, in other words, it attempts to lessen their impact. In all cases, the correction schemes are only able to handle single-bit errors within a configuration memory frame. Any multi-bit errors require full device reconfiguration. Mitigation should not be confused with immunity, or with ensuring reliable device operation—critical in medical applications. Only flash and antifuse-based FPGAs are immune to these effects and do not require mitigation to protect their configuration.

Summary

Various memory elements within electronic devices are susceptible to being upset when impacted by high-energy particles within the Earth’s atmosphere. In addition, other elements of a device may propagate induced pulses or transients that can result in errors in function. Given the potential exposure of medical devices to high neutron fluxes (due to cosmic rays as well as LINACs used in radiotherapy), designers must consider the impact of SEUs on safety and reliability.

Although estimating FIT rates for SRAM-based FPGAs within the radiotherapy environment is difficult due to the lack of specific studies, clearly the risk is not zero. Given the criticality of these applications to the life of the patient, SRAM-based PLDs are just not compatible with the reliability requirements that these applications impose.

Only one supplier of FPGAs offers devices whose base technology is fundamentally immune to configuration upset. Building on a 20-year history of delivering high-reliability products to commercial avionics, military, and space applications, Microsemi is uniquely positioned to help designers understand the impact of SEUs and SETs and mitigate their effect.

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