CHAPTER 1

Introduction

1.1 BACKGROUND

In recent years the dominant radiation effect in space-borne electronic systems has become the family of single event effects (SEEs). SEEs arise through the action of a single ionizing particle as it penetrates sensitive nodes within electronic devices. Single events can lead to seemingly randomly appearing glitches in electronic systems—frustrating errors that may cause anything from annoying (at best) system responses to catastrophic (at worst) system failures. The problem is particularly insidious due to the combination of its random nature, the omnipresent spectrum of high energy particles in space, and the increasing sensitivity of devices to SEEs as miniaturization progresses.

A SEE is a phenomenon that follows from the continuing trend in electronic device design toward higher density devices with smaller feature sizes. This trend permits faster processing of information with smaller required quantities of electric charge. As the charge involved has decreased, it has entered the region where corresponding amounts of charge can be generated in the semiconductor by the passage of cosmic rays or alpha particles. This charge can look like a legitimate signal, temporarily changing memory contents or commands in an instruction stream.

The single event upset (SEU) phenomenon was first suggested in 1962 by Walkmark [Wallmark 1962] and first reported in an operating satellite system in 1975 by Binder, Smith, and Holman [Binder 1975]. Both of these reports were generally ignored as they suggested

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responses well out of the mainstream of radiation effect studies of the time. However, in 1978, May and Wood [May 1979] reported alpha particle upsets in dynamic RAMs and Pickel and Blandford [Pickel 1978] analyzed upsets in RAM circuits in space due to heavy ion cosmic rays. It was in this time period that IBM started major on-again off-again programs with alpha emitters and terrestrial cosmic rays [Ziegler 1979, Ziegler 1981, Ziegler 1996a, and Ziegler 2004]. In 1979 Guenzer, Wolicki, and Allas [Guenzer 1979], and Wyatt, McNulty, and co-workers [Wyatt 1979] experimentally observed upsets due to high energy protons such as those present in the Earth's trapped proton belts. Gradually, as more and more upset related problems have been observed in spacecraft, SEU has come to be recognized as a very serious threat to system operations. Radiation hardening of devices and SEU tolerance approaches have alleviated the problem somewhat. It is still grave. Single event upset must be considered in all future space, missile, and avionics systems.

The early "common knowledge" of the effects was based on two papers. The paper by Binder, Smith, and Homan presented the basic information for cosmic ray induced upsets [Binder 1975]. They discussed the basic mechanisms and circuit effects, the cosmic ray environment, including the effects of shielding, and a basic approach to cosmic ray event rate. A paper by Petersen presented the proton environment with the variation in altitude and the effects of the South Atlantic anomaly and included the effects of shielding [Petersen 1981]. He then discussed the possible contributions of the various proton reactions in silicon and presented calculations of proton induced upset rates.

Much of the interest has been driven by developments such as:

- The critical errors caused by cosmic ions in the Voyager and Pioneer probes.
- The necessary retrofits, at great expense, of the Landsat D and Galileo systems due to heightened concern over single event upsets.
- The errors in the guidance system of the Hubble space telescope as its orbit carries it through the earth's radiation belts, requiring frequent scrub and reload of the guidance system.
- The loss of the Japanese satellite "Superbird" due to SEU followed by operator error [AWST 1992].

Table 1-1 lists a sampling of other space programs for which single event effects have had an impact. Some of these events were collected by Bedingfield and co-workers [Bedingfield 1996]. Ritter has also discussed some of these events [Ritter 1996].

There was a parallel set of problems for ground based systems as described by Ziegler [Ziegler 2004]. Soft errors from radiation are the primary limit on digital electronic reliability. This phenomenon is now more important than all other causes of computing reliability put together. Since chip single event rates (SERs) are viewed by many as a legal liability (selling something that you know may fail), the public literature in this field is sparse and always makes management nervous [Ziegler 2004, Preface and Chapter 1].

Table 1-1
A Few of the Spacecraft for Which Single Event Effects Have Had an Impact

For the Period 1970–1982			
DE-1	Galileo	INSAT-1	Intelsat - IV
Landsat-D	LES 8	LES 9	Pioneer Venus
SMM	Tiros-N	Voyager	
For the Period 1982–1990			
AMTE/CCE	DSCS	ERBS	Galileo Lander
GEOS-6	GEOS-7	Geosat	GPS 9521
GPS 9783	GPS 9794	HUT	IUS
MOS-1	OPEN	Shuttle	SPOT-1
TDRS-1	TDRS-4	UOSAT-2	
For the Period 1990–1997			
COBEERS-1 (SEL)	ETS-V (SEL)	ADEOS	
EUVE	HST	HST-STIS	Kitsat-1
NATO-3A	PoSAT-1	S80/T	SOHO
Spot-2	SPOT-3	STS-61	Superbird
TDRS-5	TDRS-6	TDRS-7	Topex/Poseidon
UoSAT-2	UoSAT-3	UoSAT-5	WIND
Yahkoh-BCS			
Amateur Radio Satellite Experiments			
AO-16	LO-19	I0-26	Spartan/OAST/SPRE

SEU in space originates from two sources in the natural environment. Satellites at geosynchronous orbit and corresponding regions outside Earth's radiation belts experience upsets due to heavy ions from either cosmic rays or solar flares. The natural cosmic ray heavy ion flux has approximately 100 particles/cm^2 per day. In very sensitive devices this flux can lead to daily upsets. Many devices can be upset in these environments at a rate of about 10^{-6} upsets/bit-day.

Also, upsets can occur within the proton radiation belts. Even though energy loss rates by direct ionization from protons are too low to upset most devices, proton induced nuclear reactions in silicon can result in heavy recoil nuclei capable of upsetting most memory cells. About one proton in 10^5 will undergo a nuclear reaction capable of SEU. Considering the large population of high energy protons capable of causing these reactions, proton induced upsets become a significant SEU mechanism. In the heart of the proton belts there are about 10^7 to 10^9 protons/cm^2 per day with energies above 30 MeV (approximately the minimum energy that will penetrate a spacecraft and then cause upsets). Thus, for example, a 1K memory with a proton upset cross section of 10^{-11} cm^2 per bit would have 10 upsets per day in the most intense part of the belt.

As the cosmic rays penetrate the atmosphere, there is a chain of nuclear reactions that produce high energy neutrons and protons. A nominal figure is 6000 neutrons per square centimeter per hour at 40,000 feet altitude and 45 degrees latitude. In the 1990s these were shown to produce single event upsets in complex integrated circuits in avionics equipment.

There are a variety of possible single event effects (SEEs). These are important as they can cause malfunctions in microelectronics devices operating in the space ionizing radiation environment. The principal effects are upset, transients, and latchup, but the others need also to be kept in mind. The basic effects are as follows:

SEU	UPSET	Temporary change of memory or control bit
SET	TRANSIENT	Transient introduced by single event
SEL	LATCHUP	Device latches in high current state
SES	SNAPBACK	Regenerative current mode in NMOS
SEB	BURNOUT	Device draws high current and burns out
SEGR	GATE RUPTURE	Gate destroyed in power MOSFETs
SEFI	FUNCTIONAL INTERRUPT	Control path corrupted by an upset
MBU	MULTIBIT UPSET	Several bits upset by the same event

Single events acquire that name because they depend on the interaction of a single particle. Most other radiation effects depend on the dose or damage deposited by large numbers of particles. SEEs can be caused by the passage of a single heavy ion—a cosmic ray in space, for example. As the cosmic ray passes through the silicon of the device, it deposits a track of ions. In space the cosmic rays are ordinarily energetic enough that they pass through the device. If these resulting ions are in the presence of the natural or applied field in an electronic device, they are collected at the device electrodes. See Figure 1-1. This produces an electric pulse or signal that may appear to the device as a signal to which it should respond. If the electrical characteristics of the device are such that the signal appears valid, then there may be a bit upset or the production of a signal in a logic device that triggers a latch later in the device.

High energy protons can also initiate single event effects. It is not the proton passage that produces the effect. The proton itself produces only a very small amount of ionization. Very few devices are sensitive enough to respond to the proton ionization. However, 1 proton in 10^5 will have a nuclear reaction in the silicon device. These reactions can produce heavy ions that in turn can deposit enough energy to cause upset. See Figure 1-2. Although this seems like a very small number of cases, in space the protons in the proton radiation belts are intense enough so that they can cause many more upsets than the heavy ion cosmic rays in the same environment.

The basic concepts are similar for both heavy ion and proton induced upsets. The prime emphasis in the present work is the heavy ion induced upsets. We will also discuss proton and neutron upsets for comparison later. The prediction of single event effect rates depends on

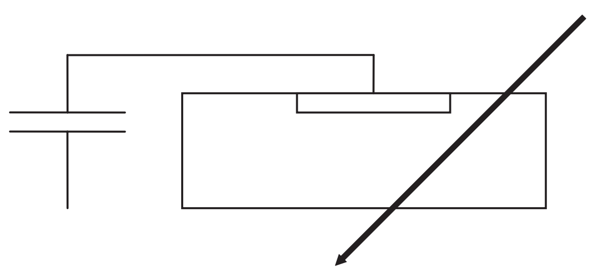

Figure 1-1 Ionization path due to direct passage of a heavy ion.

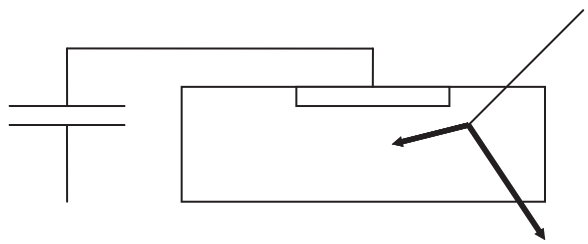

Figure 1-2 Ionization paths due to proton reaction in a device.

a number of independent models of various aspects of the phenomena involved.

Single event effects can be thought of as one of nature's ways of enforcing Murphy's Law. They can occur at any time, at any place in an electronic system. They do not depend on the cumulative exposure to the space environment and are as likely to occur during or shortly after launch as after a long time in orbit. As for location, the sorrowful words of one space system designer express it: "I know that you said I was going to have upsets, but I didn't expect an upset in *that* bit."

Because of these and other real world problems in space systems due to cosmic ions, an understanding of single particle errors in integrated circuit (IC) electronics has become an important part of the design and qualification of IC parts for space-based use.

The issue becomes even more important as device dimensions scale, and denser, more powerful integrated systems are placed in space or satellite applications. Electronics is reaching integration levels where a single bit of information is represented by an extremely small value of charge, and noise margins are very tight. For example, if a typical dynamic random access memory (DRAM) cell can tolerate approximately 100 mV of noise on the bit storage node with 100 fF (10^{-15} farads) of storage capacitance, then this value of noise corresponds to a charge of only 62,500 electrons. Any perturbation of this delicate balance by an impinging cosmic ion is intolerable. So, a recognition of, and familiarity with, the effects of space radiation on the electronics to be placed in that hostile environment is essential. Single event modeling plays a key role in the understanding of the observed-error mechanisms in existing systems, as well as the prediction of errors in newly designed systems.

There are two different aspects of interest. First is the analysis of various types of single event experiments to help understand the phenomena. Second is the modeling of the various aspects of the phenomena that allow prediction of SEE rates in space.

1.2 ANALYSIS OF SINGLE EVENT EXPERIMENTS

1.2.1 Analysis of Data Integrity and Initial Data Corrections

Single event experiments involve a mixture of electronic measurements and nuclear physics experimental techniques. This leads to a number of possible errors in the measurements, some of which are not common in standard electrical engineering experiments. Therefore, the first step in the analysis of SEEs data is the examination of the integrity of the data itself.

There are some aspects of the data that are an artifact of experimental approach. The data needs to be corrected for these before it is used for analysis and prediction.

1.2.2 Analysis of Charge Collection Experiments

The initial studies of SEEs assumed that it took a unique amount of charge to cause the effect. This corresponded to a step function as one examined device sensitivity as a function of energy deposition. The energy deposition was measured by the linear energy transfer (LET) of the ionizing particle (see Section 2.2). However, all of the experiments indicted an “S” curve of the variation of SEE rate as a function of LET. It was initially assumed that this was caused by a variation from memory cell to memory cell. Then a number of charge collection experimental and theoretical studies indicated that the variation in sensitivity corresponded to a variation across the transistor and across the memory cell.

1.2.3 Analysis of Device Characteristics from Cross-Section Data

The SEE cross-section curve is a reflection of the various charge collection processes and circuit characteristics that are involved in the

SEE. Study of the characteristics of this curve gives some insight into the processes involved in a particular device.

1.2.4 Analysis of Parametric Studies of Device Sensitivity

There are a large number of device parameters that can be adjusted when testing the device. These may be parameters that affect device design, or factors corresponding to different modes of operation in space. The variation in the experimental cross sections with parametric changes gives a direct measure of the space SEE rates dependence on these factors.

1.3 MODELING SPACE AND AVIONICS SEE RATES

1.3.1 Modeling the Radiation Environment at the Device

This involves modeling the proton and heavy ion radiation environment in space and the neutron environment in the atmosphere. (We will often refer to modeling in space, with the understanding that the discussion refers to both space and avionics environments.) The sources are cosmic rays, solar particles, and geomagnetically trapped radiation. Basic factors are intensities, elemental compositions, and energy distributions. The environment at the device is influenced by the component material shielding surrounding the device, geomagnetic shielding effects (which depend on orbit parameters), and time variations associated with the solar cycle. For single event effects by heavy ions, it is really the energy loss characteristics of the environment that are important. Therefore, the cosmic ray composition and energy variation are translated to the number of particles as a function of their energy loss per unit path length (dE/dX), normalized to the material and called linear energy transfer (LET). The LET spectrum can be expressed in either a differential form (number of particles with given energy loss) or in an integral form (number with energy loss greater than a given LET).

1.3.2 Modeling the Charge Collection at the Device

The upset depends on the amount of charge that the electronic circuit detects. This in turn depends on the amount of charge deposited by the ion. It is not sufficient for an ion to hit a device or an individual nucleus in the device, but instead it must have an appreciable track length. The amount of charge deposited depends on the product of the path length and the LET of the ion. Therefore, one must model the sensitive volume of the device. That is, you must know the area, depth, and shape of the sensitive region. With this information, the distribution of possible path lengths in the device can be modeled. These path length distributions can be expressed in either a differential or an integral form, that is, number of paths of a given length, or number of paths that equal or exceed a given length.

The charge collection may be complicated by the fact that there are several possible charge collection processes that can take place. The charge may be collected by the intrinsic and applied field along the track in the device itself. There may be additional charge collected as charge diffuses into the device. It is also possible that the fields are distorted along the ion track, leading to additional charge in the track being brought into the device.

1.3.3 Modeling the Electrical Characteristic and Circuit Sensitivity for Upset

The circuit that the device is embedded in determines what the applied pulse shape must be if it is to appear as a legitimate electrical signal. In most cases, these effects can be modeled by standard SPICE circuit modeling of the circuit. In some case, there are more complicated interactions between the charge collection and the circuit, so that the effects are better modeled if considered together.

It is not always possible to obtain enough information about the detailed device characteristics to perform electrical modeling. It has now become common to base the estimates of device sensitivity on experimental upset measurements in the laboratory.

The prediction of rate effects that occur in space then depends on models that include three basic factors: the environment, the device dimensions, and the device sensitivity. There are possible complications that involve the details of the shape of the device sensitive volumes and of the charge collection. We will analyze the various approaches to upset rate predictions, and examine how they consider both the basic factors and the complications.

One of the modeling complications that we will discuss is the treatment of charge collection in the device. The basic aspects of charge collection are included in all models. However, there are a number of possible complications that can have a significant impact on the interpretation of experimental data. These factors can also sometimes impact the rate predictions. These factors will be introduced where appropriate.

1.4 OVERVIEW OF THIS BOOK

We present an overview of the various factors and approaches that are important for single event effect measurements, rate modeling, and predictions. We then develop the concepts that are important for rate prediction, develop the history of rate predictions, outline the approaches that have developed, and present standards that are being developed. We have an extensive discussion of the interpretation of experimental results. We will also discuss some of the issues that remain.

One of the possible complications is the charge collection in the device. The basic aspects of charge collection are included in all models. We will consider the charge collection as it shows up in the cross-section measurements, but not consider the various detailed micromodeling approaches to the problem.

The book presents an overview of the methods and procedures involved in computer modeling of single event phenomena that have been proposed and utilized in recent years. The goal of these procedures is to model the interaction of a radiation environment with microelectronic circuits, and to predict the resulting influences on proper IC operation.

This book is based on published materials but does include some new material and some new examples. We hope that some of the examples will be helpful for newcomers in the field. Other examples are aimed at those experienced in the field who we believe have misunderstood some of the concepts of the integral rectangular parallelepiped (IRPP) approach to upset rate calculations.

1.5 SCOPE OF THIS BOOK

This book is intended to be a tutorial, covering the basic terminology and concepts of single event effects and rate prediction. It is based on the notes for 2008 NSREC Short Course with additions, corrections, and indexes [Petersen 2008b]. It is hoped that it presents enough information for the reader to find the relevant literature of a specific topic of interest so that he/she can study it in depth. The book will go into some depth on the issues that lay at the foundation of the subject or that are important for SEU measurements or for the interpretation of SEU measurements. Attention is paid to a number of experimental aspects from nuclear physics that may not be covered in electrical engineering courses. In some sections we may go into too much detail for the reader. Skip those sections until you need them.

There is little discussion of the actual effects in devices or circuits. It is possible to write a book or major review article on modeling and simulation of the electronic aspects of single event effects that has virtually no overlap with this book [Fleetwood 2004, Lacoe 2008, Munteanu 2008, Pease 2008]. The electronic modeling has been well presented in an IEEE NSREC (Institute of Electrical and Electronics Engineers, Nuclear and Space Radiation Effects Conference) short course by Lloyd Massengill [Massengill 1993c]. The short course presentation of Sexton is also highly recommended [Sexton 1992]. A very good update of Massengill is given by Black and Holman [Black 2006]. Reed discusses some of the basic physics underlying the electrical effects [Reed 2008].

There is a wealth of information in important IEEE NSREC short course presentations and other reviews. [Benedetto 2008, Bourdarie 2008, Hafer 2008, Munteanu 2008, Petersen 2008b, Reed 2008, Wilkinson 2008, Kastensmidt 2007, Ladbury 2007a, Black 2006, Law 2006, Santin 2006, Xapsos 2006b, Bauman 2005, Buchner 2005, Cressler 2003, Oldham 2003, Weatherford 2002, Buchner 2001, Hoffmann 2000, Dodd 1999, Dressendorfer 1998, Barth 1997, Petersen 1997b, Alexander 1996, Galloway 1996, Ritter 1996, Stapor 1995, Normand 1994a, Massengill 1993c, Sexton 1992, McNulty 1990, Petersen 1983c, Pickel 1983]. The reader who wants a comprehensive background in single event effects should study these. At the same time, be aware that our knowledge has been changing continuously. The material in this book has been changed significantly from the corresponding material in 1997 [Petersen 1997b].