

Single Event Phenomena: Testing and Prediction

James D. Kinnison
The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723
jdk@aplcomm.jhuapl.edu

Abstract - Highly integrated microelectronic devices are often used to increase the performance of satellite systems while reducing the system power dissipation, size, and weight. However, these devices are usually more susceptible to radiation than less integrated devices. In particular, the problem of sensitivity to single event upset and latchup is greatly increased as the integration level is increased. Therefore, a method for accurately evaluating the susceptibility of new devices to single event phenomena is critical to qualifying new components for use in space systems. This evaluation includes testing devices for upset or latchup and extrapolating the results of these tests to the orbital environment. Current methods for testing devices for single event effects are reviewed, and methods for upset rate prediction, including a new technique based on Monte Carlo simulation, are presented.

1 Introduction

Satellite system designers are constantly seeking new technology to increase the performance of their systems. Many new VLSI devices are well suited to space applications. For example, telescopes flown on spacecraft have greatly benefited from the use of on-board digital signal processors. However, space contains many hazards for which most VLSI devices have no inherent immunity. To be used in a satellite application, the response of these integrated circuits to the various space hazards must be measured, and some estimate of the survivability of these devices must be made.

One of the most difficult problems facing integrated circuits is that of exposure to charged particles. As these particles pass through a material, they lose energy by ionizing the material, inducing electron-hole pairs along the path of the particle. The interaction of electrons, protons, and heavy ions with integrated circuits leads to two different kinds of problems. The first is total dose degradation, in which the cumulative effect of many particles passing through an integrated circuit causes parameter degradation and functional failure, and will not be considered here. In addition to this problem, single particles passing through a device may cause a variety of effects, collectively known as single event phenomena (SEP).

In digital devices, the most common phenomenon is single event upset, in which the state of a bit or an active node is reversed. This erroneous state remains until that bit or node is reset. CMOS devices are susceptible to ion-induced latchup, similar to input latchup commonly observed on the workbench. In this case, a charged particle traverses a p-n-p-n region, and the induced current pulse injects enough minority carriers into the parasitic transistors present in the structure to cause a low impedance path from supply to ground.

Latchup is usually destructive. Analog or mixed analog-digital devices are susceptible to current pulses injected by charged particles. These pulses are short-term transients which can propagate to other devices and cause a bewildering array of system-level effects. Finally, power MOSFETs are susceptible to burnout and gate rupture due to charged particles, described first in [1].

2 General Considerations

The effects discussed above are nominally different, but have a core of similarity. In each case, the effect is initiated by a single charged particle traversing a sensitive region of a device. In the simplest case, a monoenergetic beam of particles irradiating a device, some particles deposit enough charge in a sensitive region to cause an event (i.e., an upset, latchup, or transient). The number of events occurring, N , is given by

$$N = \rho * n \quad (1)$$

where ρ is the probability that a particle causes an event, and n is the number of particles passing through the device. Normally, the number of interactions is given in terms of the particle fluence, the number of particles per unit area, instead of the number of particles. If we multiply ρ and divide n by the area of the device, the previous equation becomes

$$N = \sigma * \Psi \quad (2)$$

where σ is the event cross-section, with units of area, and Ψ is the particle fluence.

In principle, the cross-section contains all the information about an integrated circuit necessary to estimate the event rate in any environment. For each type of event, the cross-section depends on many factors, including angle of incidence, the type and energy of the incoming particle, the temperature, and the electric fields present near the sensitive regions. In some cases, it is possible to assign a physical meaning to the cross-section. For example, in a static RAM, each cell is nearly identical, and contains a nearly identical sensitive volume. If a particle induces enough charge in one of these volumes, an upset occurs in that cell. The cross-section is just the area of the sensitive volume normal to the particle path.

In the case of heavy ions, it is convenient to describe the event cross-section as a function of the incident particle linear energy transfer (LET), rather than particle type and energy. The linear energy transfer is the amount of energy transferred to the target material along the particle path, and is the derivative of the energy with respect to distance along the track. LET is usually given in units of MeV*cm²/mg, and is determined by the incident particle type, charge, and energy, and by the target material density. The cross-section for a device is zero below some LET normally referred to as the threshold LET, and rapidly increases to a value called the asymptotic cross-section. For SEP due to protons, the cross-section is determined as a function of incident proton energy rather than LET, but the form of the cross-section remains the same.

For many devices, the angular dependence of the cross-section is easily expressed. A particle which travels through a device at some oblique angle has a longer path through the device than a particle which travels normal to the device; therefore, more energy is

transferred to the target material. The result is a particle which appears to have a larger LET than the same particle at normal incidence. Therefore, the LET of the particle is expressed as an effective LET given by

$$L_{eff} = \frac{L}{\cos\theta} \quad (3)$$

Note that this does not account for azimuthal asymmetry of the device, and so does not give the azimuthal dependence of the cross-section. This dependence is measured by irradiating the device at several azimuthal angles.

The cross-section of a device can sometimes be estimated using a computer model. This obviously requires in-depth knowledge of the device layout which is not usually available to the user. In most cases, the cross-section must be measured. These tests are usually performed at a particle accelerator laboratory; one of the most commonly used sites is the Tandem Van de Graaff accelerator at Brookhaven National Laboratory. No matter where the test is performed, the layout is much the same. The accelerator provides a beam to a target area with the same LET (or in the case of protons, energy) as particles found in space. Since the path length of heavy ions in air is very short, the target area is usually a vacuum chamber connected to an evacuated beam line. The device under test (DUT) is mounted in the target area, irradiated with particles, and tested for events. Since the beam is monoenergetic, and the particle fluence over the exposure is measured, equation (2) can be used to calculate the cross-section. This procedure is repeated for a variety of test conditions, until the cross-section is completely characterized.

3 Test Methods

Nearly all SEP cross-section measurements are performed in the manner outlined above. The main differences occur in the ways that logistical problems for a target area are solved. For example, nearly all SEP tests are computer controlled, but the tests must be performed in a vacuum chamber. Therefore, the problem of communicating with a DUT or test hardware through vacuum feedthroughs must be solved. Similarly, DUTs dissipate heat when operated; in a vacuum chamber, good thermal control is essential.

The integrated circuits under consideration are usually quite complex, and the problem of exercising the device while looking for errors is challenging, to say the least. While there are many ways to implement a test for SEP events, they all fall into four categories, the squirt, golden-chip, pseudo-golden-chip, and loosely coupled methods. There are benefits to each method, but none is appropriate for all device types. Therefore, an understanding of all four is essential to planning a good SEP test [2].

3.1 Squirt Method

The squirt method is the simplest way to test for SEP. In this type of test, a device is prepared for exposure, irradiated, and then interrogated for the presence of events. In general, the DUT is under static bias, and only SEP which are not time dependent are considered.

As an example, consider upsets in a static RAM. The test hardware consists of a circuit which loads a fixed pattern into the memory, then reads back the contents of the memory and compares this to the original. The cross-section is calculated by counting the total number of upset bits and dividing by the particle fluence over that exposure. This sequence is repeated for a variety of particles with different LET and incident angle, and for a number of other device conditions such as bit pattern and temperature.

Latchup or burnout tests are often performed using this method. In this case a device is irradiated under static bias; after exposure, the device is examined for latchup or burnout. Since the latchup could have occurred during any part of the irradiation, the results of this test can not be used to calculate the latchup cross-section, but the susceptibility of a device to a particle of a particular LET is determined.

Obviously, this type of test is easy to implement, and for many devices, is quite adequate as a screen for destructive phenomena. However, this type of test is usually incomplete in the sense that only static errors are counted. In the case of the static RAM, for instance, those portions of the device which provide control and address decoding are never tested. Since one error in control logic may upset many bits at once, this oversight may gloss over grossly undesirable behavior. Other significant behavior, such as the device operating frequency dependence of the event cross-section, may also be missed. Finally, sensitive bits may flip more than once during an exposure. If this occurs, an error may never be counted, or may only be counted once, and so the cross-section may be too low by a factor of two or three. Despite these drawbacks, there may be times when this type of test is appropriate. The upset cross-section of many memories is still measured this way, since cell upsets dominate the cross-section.

3.2 Golden-Chip Method

Since static tests can miss some types of events, dynamic testing is preferred for SEP measurements. The golden chip method is a way to implement these dynamic tests without building a large VLSI integrated circuit tester that fits in a vacuum chamber. The test hardware is built around two identical devices which are mounted so that one is irradiated while the other is not. If the devices are given the same inputs, they should have the same outputs, unless an event occurs. Therefore, the error detection consists of a set of level comparators, one for each output, and a counter which keeps track of the number of events observed. In addition, the control hardware must be able to simultaneously reset the test device and the golden device when an error occurs.

Golden-chip tests offer one important advantage over the previous type; the test is dynamic, not static. Therefore, all portions of a circuit can be exercised. In addition, events are counted dynamically, so missed multiple events are much less likely. The golden-chip method can be used to test many different kinds of logic devices which operate at relatively low frequency and with a small number of inputs. For example, latchup tests can be performed by comparing the supply current and outputs of an irradiated device to those of a golden device. When a large difference in the supply current is observed, a latchup has occurred.

However, there are limitations to the usefulness of this method. First, the test hardware

must provide inputs to the devices simultaneously. Second, the number of input states in a test cycle determines the amount of data storage needed in the test control hardware; for some devices, the number of inputs needed to effectively exercise all portions of the DUT can be quite large. Third, the devices should not be overly sensitive to noise, which on an output could be mistaken for an event. Finally, the device outputs, including timing parameters, must be identical to within the resolution of the tester comparators. In most cases, this restriction imposes an upper limit to the DUT operating frequency during the test.

3.3 Pseudo-Golden-Chip Method

The pseudo-golden-chip method seeks to avoid the limitations of the golden-chip method by comparing the output sequence of the DUT to some standard sequence. In essence, we replace the golden device with a computer. As the DUT is irradiated, each output is compared to an expected value. Any discrepancy is counted as an event.

A good example of a device suited to this test method is a FIFO memory. A known bit pattern is repeatedly applied to the FIFO, and after each write, a word is read. If the correct pattern does not appear, then a single event upset has occurred in either the control logic or the circular buffer in the FIFO.

This type of test is frequently used in SEP testing. Most groups who regularly test devices for SEP susceptibility have developed some type of computer-based test hardware which can rapidly be tailored for this kind of test. As with the golden-chip method, the number of different states in the input sequence limits the usefulness of this tests. The operating frequency of the DUT is also limited by the time taken to compare all the DUT outputs to the expected values.

3.4 Loosely Coupled Systems Method

All three methods discussed above are based on some set of test hardware closely controlling and examining a device. This is, in principle, the best way to test for SEP. In practice, however, an event in a DUT can cause the test hardware to malfunction. This is disastrous in an SEP test; any dead time, in which the beam is on but events cannot be counted, artificially reduces the accuracy of the cross-section measurement. Therefore, it is essential that the test system is able to quickly detect and correct any events observed in the DUT.

The loosely coupled systems method is built around the interaction of two systems. The first system, which I will call the DUT test system is used to exercise the DUT. The second system, called the test controller, is used to monitor for events reported by the DUT test system, and to reset the DUT test system when an event is observed. The two systems communicate asynchronously.

This method is the most effective way to test microprocessors and related devices. In this case, the DUT test system would be a single board computer which executes some fixed test routine on bootup. This routine is written so that a known status word, which indicates whether the DUT test routine was completed successfully or an event occurred, is sent to the test controller computer at regular intervals via a serial link or some similar communication protocol. The test controller receives the status word, examines it, and forces a reset in the

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DUT test computer if an event is detected. In addition, the test controller operates as a watchdog so that if an event in the DUT stops the operation of the DUT test system, a reset is forced.

In spite of the benefits discussed above, there are problems with this method. First, some information about the distribution and effect of event in the DUT is lost. We can determine that an event occurred, but not where or exactly what the consequences of that event are in the DUT. Second, the cross-section measured is really the cross-section of the DUT test system, not the DUT; if only the DUT is irradiated and all events which occur in the DUT are observed, then the system event cross-section is a close approximation to the DUT cross-section. Third, because the devices tested in this manner are complex, the cross-section may vary significantly with test program. Because of these problems, the DUT test system should be as close to the target application as possible.

4 Rate Prediction

The cross-section for some event is a parameter used to characterize the susceptibility of a device to that event. It contains all the information needed to estimate the event rate in an arbitrary charged particle environment. The methods by which these estimates are calculated, however, are not simple, and much research into event rate prediction methods has been centered around simplifying the calculation of event rate estimates.

Unfortunately, some methods developed for one type of event may not be applicable to other types of events. Most of the effort has been directed toward developing single event upset prediction methods. Only recently have researchers started examining other effects and the relationship between the cross-sections for different effects. The most important event rate prediction methods are discussed below.

4.1 The Path-Length Distribution Model

The path-length distribution model assumes that every upsetable cell in a device is identical, and that each contains one thin rectangular parallelepiped region, called the sensitive volume, such that a particle which deposits charge in this region may cause an upset. If this is true, the upset rate, N , is given by

$$N = 22.5\pi A Q_C \int_0^{\infty} \frac{D[p(L)]}{L^2} \psi(L) dL \quad (4)$$

where A is the area of the sensitive volume, Q_C is the smallest deposited charge that will cause an upset (called the critical charge), L is LET, $D[p(L)]$ is the differential distribution of path lengths over which a particle of LET, L , will produce a charge greater than the critical charge, and ψ is the integral flux spectrum given as a function of LET. Pickel and Blanford [3], in 1980, originally proposed an integral of this form for the error rate.

All of the parameters in (4) are given by the cross-section except the particle flux. The critical charge is just the threshold LET in units of $pC/\mu m$ (which is equivalent to $MeV \cdot cm^2/mg$) times the minimum thickness of the sensitive volume (in μm). A is the asymptotic cross-section. The differential path length distribution depends on the shape of

the sensitive volume, and is not simply expressed. In most cases, the sensitive volume is assumed to be a rectangular parallelepiped, and the appropriate path-length distribution is used to evaluate (4)

The path-length distribution model was developed to predict single event upset rates in memories. The assumptions used to write (4) approximate most static RAMs to first order. However, many devices are not so simply described. For instance, a microprocessor may contain many different upsetable nodes, each with a unique sensitive volume. The result is that each node may have a different threshold and asymptotic value. The cross-section, as measured in SEP tests, is the sum of the responses of each individual sensitive volume. The integral in (4) does not model these situations well, but it is possible to increase the accuracy of the calculation for some devices which do not have identical sensitive volumes. If the individual sensitive volumes can be separated into a small number of groups with nearly identical volumes in each group, error rates can be calculated for each group. The total device error rate is just the sum of the group error rates.

Only single event upsets are considered in the path-length distribution model; the assumptions concerning the shape and uniformity of the sensitive volume only apply to single event upset. In other cases, particularly latchup, the concept of a sensitive volume is not meaningful, and so an equation like (4) cannot be written.

Several computer programs have been written to estimate the single event upset rate of a device using the path-length distribution model. The first of these was *Cosmic Ray Induced Error Rate Analysis* (CRIER) by Pickel and Blandford [4]. In 1981, Adams, Silverberg, and Tsao published the first part of a new model of the galactic cosmic ray environment. Over the next three years, they added the effects of the Earth's magnetic field to the model, and included a program to calculate the single event upset rate of a device in an arbitrary environment by evaluating (4). This model is called *Cosmic Ray Effects in Microelectronics*, also known as CREME [5]. CREME is commonly used today for single event upset rate estimations.

4.2 The Bendel Proton Upset Models

It is commonly known that galactic cosmic rays cause single event upsets. Less commonly known is that high energy protons found in the Van Allen radiation belts can also cause single event upsets. These protons do not produce enough ionization to upset a device directly, but secondary particles created in nuclear reactions with the target material can produce sufficiently high ionization to cause upset. The Bendel models provide an estimate of the upset rate due to proton nuclear reactions in a variety of low Earth orbits as a function of semi-empirical fit parameters.

The first model is called the one-parameter Bendel model [6]. The proton upset cross-section is measured at a few proton energies, and then fitted to the following equations to solve for A:

$$\sigma = (24/A)^{14} [1 - \exp(-0.18Y^{1/2})]^4 \quad (5)$$

$$Y = (18/A)^{1/2} (E - A) \quad (6)$$

where E is the proton energy and σ is in units of 10^{-12} upsets per proton/cm² per bit. An estimate of the proton upset rate as a function of orbit altitude and inclination, and as a

function of the parameter A is given in [6]. This semi-empirical model works reasonably well for older devices, but needs improvement for newer, more complex technology.

To increase the accuracy of the method, Stapor, et al. [7] have recast (5) as a two parameter model. The equation becomes

$$\sigma = (B/A)^{14}[1 - \exp(-0.18Y^{1/2})]^4 \quad (7)$$

where Y and σ are defined as in (5)-(6). As before, an estimate of the proton upset rate as a function of altitude and inclination, and as a function of both parameters, A and B, is given in [7].

Estimates made with the two parameter Bendel model have been compared to flight data taken on the CRRES satellite. These estimates are in reasonably good agreement with the flight data [8]. However, the estimates provided by the Bendel models are averages over a very dynamic environment, and the short term error rate may be much higher than the estimate. Therefore, systems with devices susceptible to proton upset must be able to withstand short periods of greatly increased error rate.

4.3 Probabilistic Model

The definition of a cross-section given in (1)-(2) is based on a probabilistic interpretation of the interaction which causes SEP. Consider a monoenergetic beam of particles with direction normal to the face of a device. If the beam is uniform, the probability that a particle intersects the device at a particular point is constant across the face of the device. Assume that some regions of the device are sensitive to an event; any particle passing through those regions will cause an upset. The probability that a particle passes through these regions is just the total area of the sensitive regions divided by the area of the device. The total area of the sensitive regions is given by the cross-section.

In space, the particles interacting with the device are not monoenergetic, and so not all have the same LET. In addition, the particle flux is omnidirectional; the particles arrive from every direction at the same rate. So, for a particle of a given LET and direction, the probability that an event occurs is just the cross-section for that LET and direction divided by the projected area of the device normal to the particle direction.

The probabilistic nature of the cross-section can be exploited to calculate an event rate for a device in a particular environment using a Monte Carlo simulation [9]. For a calculation of this nature, only the event cross-section as a function of LET and incident direction and the fluence as a function of LET are needed. The flux spectrum is divided into narrow LET bins. For a particle in one of the bins, the basic algorithm is as follows:

1. Pick a random LET within the bin.
2. Pick a direction.
3. Calculate the cross-section based on the LET and direction.
4. Generate a random number.
5. If the random number is less than the cross-section, increment the event count.

The event rate estimate is given by the event count which results after repeating the algorithm for the total number of particles in each LET bin of the flux spectrum.

The algorithm given above is applicable to any SEP for which a cross-section can be measured. Event rates generated by this type of computer simulation compare well with CREME and Bendel model estimates and with flight data. The advantage of this method is that no information about the geometry or architecture of the device is necessary to generate a good estimate of the event rate.

5 Current Research

Several areas of current research in SEP may lead to new test and estimation techniques which will simplify the problem of qualifying new devices for use in space. These new techniques include new ways to stimulate devices to produce SEP, methods of estimating the cross-section for one type of event from the cross-section of another type, and new models for estimating event rates from cross-section data.

Accelerator beams are not cheap, and it can be difficult to schedule an experiment in a timely fashion. In addition, few researchers are located near an accelerator; experiments must be transported to the accelerator facility. Because of these difficulties, some researchers are using radioactive isotopes to provide high LET, low energy particles in a small vacuum chamber as an alternative stimulus for SEP. The most commonly used isotope for SEP testing is ^{252}Cf , which produces fission fragments with a mean LET of $43 \text{ MeV}\cdot\text{cm}^2/\text{mg}$. Unfortunately, these fragments have a limited range in silicon; they lose a significant fraction of their total energy in about $25 \mu\text{m}$. Therefore, this type of testing works reasonably well for single event upset testing, but is not useful for latchup, which requires deeper penetration into the device. In addition, as the particle travels deeper into the device, the LET changes as energy is lost. This effect must be taken into account when assigning an LET to the fission fragments. In spite of the disadvantages, ^{252}Cf is commonly used to compare the relative sensitivity of devices, and to supplement accelerator tests.

Several groups are examining the use of pulsed lasers to simulate the effects produced by charged particles in devices [10]. A narrowly focussed laser beam produces localized electron-hole pairs in the target material like an ion. The effective LET of the laser beam can be varied by changing the intensity of the laser, so a wide LET range can be simulated. The primary advantage of using a laser beam to stimulate SEP is that the spot size is of the same order as the feature size. Therefore, sensitive regions of the device can be mapped accurately, and geometrical assumptions about the sensitive volume are not necessary. Unfortunately, metal layers reflect the laser light, and so regions under metal can not be tested; the cross-section given by laser exposures is not complete, and can not be used in event rate calculations. However, the information gathered using a laser can be used to identify SEP sensitive regions so that device designers can correct the problem.

Solid-state detectors have been used in nuclear and radiation physics experiments for some time. In many ways, an integrated circuit may be viewed as a collection of solid state detectors. McNulty, et al, [11] have characterized the charge collection properties of many integrated circuits, and have shown that these measurements can be used to calculate the single event upset cross-section of a device. In a test of this type, the DUT is biased such

that the inputs and output are floating, supply pins are grounded, and the ground pins are connected to pulse height analysis system. When the device is exposed to a particle beam, charge is collected; the passage of a single particle is seen as a current pulse. These pulses are collected and sorted by the pulse height analyzer into a pulse spectrum. Peaks in this spectrum represent sensitive regions in the device, and the area under a peak divided by the total fluence over the exposure is the cross-section of the sensitive region which generated that peak. This technique may be used to map sensitive volumes, so geometrical assumptions are not necessary to calculate an event rate. To date, this technique has only been used to measure single event upset cross-sections in regular structures, like static RAMs. A complex device such as a microprocessor may not be tested well with charge collection techniques. In addition, this is a static test, which can not be used while dynamically exercising a device. It is not clear that this test will accurately measure a cross-section that depends on frequency, program, or other dynamic variables.

A group led by Newberry has recently begun examining the relationship between device upset rates and system-level upset rates [12]. She has shown that, for some systems, single event upsets which occur in a device in that system are not propagated to the system output, and that, for other systems, device upsets are multiplied and spread throughout the system. This indicates that the upset rate of a system may not be the sum of the upset rates for each component of the system. If this is true, methods for simulating the effect of upsets on system behavior must be developed. In addition, this behavior may force experimenters to test for events at the system level, instead of the device level; entirely new test methods will have to be developed.

6 Summary

Satellite systems will continue to grow more complex, and the problem of SEP susceptibility will not go away. Therefore, it is critical that space systems designers understand the behavior of new integrated circuits in the space environment. I have discussed the methods which are commonly used to assess SEP vulnerability and to estimate the rate at which SEP occur in an orbital environment. SEP tests can be grouped in four classes of test types. Each of these test types have benefits and drawbacks, and an understanding of each test type is necessary to effectively gather the data necessary to predict the rate at which SEP occur in space.

In addition to the test types, I have discussed the most commonly used methods used to calculate estimates of the SEP rate in any environment. The assumptions upon which each of the methods are based are given, and the range of applicability is discussed.

Finally, some of the newest areas of SEP research are discussed. These research areas give some indication of the direction future SEP tests will take. Of critical importance will be the way system-level SEP tests are performed, and how these tests will be used to estimate the performance of a complex system in space.

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