METRIC
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Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices [Metric][1]

This standard is issued under the fixed designation F 1192M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide defines the requirements and procedures for testing integrated circuits and other devices for the effects of single event phenomena (SEP) induced by irradiation with heavy ions having an atomic number $Z \geq 2$. This description specifically excludes the effects of neutrons, protons, and other lighter particles that may induce SEP via another mechanism. SEP includes any manifestation of upset induced by a single ion strike, including soft errors (one or more simultaneous reversible bit flips), hard errors (irreversible bit flips), latchup (permanent high conducting state), transients induced in combinatorial devices which may introduce a soft error in nearby circuits, power field effect transistor (FET) burn-out and gate rupture. This test may be considered to be destructive because it often involves the removal of device lids prior to irradiation. Bit flips are usually associated with digital devices and latchup is usually confined to bulk complementary metal oxide semiconductor, (CMOS) devices, but heavy ion induced SEP is also observed in combinatorial logic programmable read only memory, (PROMs), and certain linear devices that may respond to a heavy ion induced charge transient. Power transitors require a special test approach that has not yet been formalized.

1.2 The procedures described here can be used to simulate and predict SEP arising from the natural space environment, including galactic cosmic rays, planetary trapped ions and solar flares. The techniques do not, however, simulate heavy ion beam effects proposed for military programs. The end product of the test is a plot of the SEP cross section (the number of upsets per unit fluence) as a function of ion LET (linear energy transfer, or ionization deposited along the ion's path through the semiconductor). This data can be combined with the system's heavy ion environment to estimate a system upset rate.

1.3 Although protons can cause SEP, they are not included in this guide. A separate guide addressing proton induced SEP is being considered.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Terminology

2.1 *Definitions of Terms Specific to This Standard:*

2.1.1 *californium-252 source*—californium-252 is a fissionable isotope used for heavy ion tests, emitting fission particles with a bimodal mass distribution and bimodal energy spectrum having a mean LET of ~45 MeV/(mg/cm^2). Alpha-particles accompanying the fissions can be used for source strength determinations.

2.1.2 *DUT*—device under test.

2.1.3 *fluence*—the flux integrated over time, expressed as ions/cm^2.

2.1.4 *flux*—the number of ions/s passing through a one cm^2 area perpendicular to the beam (ions/cm^2-s).

2.1.5 *LET*—the linear transfer, also known as the stopping power dE/dx, is the amount of energy deposited per unit length along the path of the incident ion, typically expressed as MeV-cm^2/mg.

2.1.5.1 *Discussion*—LET values are obtained by dividing the energy per unit track length by the density of the irradiated medium. Since the energy lost along the track generates electron-hole pairs, one can also express LET as charge deposited per unit path length (for example, picocoulombs/micron) if it is known how much energy is required to generate an electron-hole pair in the irradiated material. (For silicon, 3.62 eV is required per electron-hole pair.)

A correction, important for lower energy ions in particular, is made to allow for the loss of ion energy after it has penetrated overlayers above the device sensitive volume. Thus the ion's energy E at the sensitive volume is related to its initial energy E_O as:

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$$E_s = E_o - \int_{o}^{(t/\cos\theta)} \left(\frac{dE(x)}{dx}\right) dx$$

where t is the thickness of the overlayer and θ is the angle of the incident beam with respect to the surface normal. The appropriate LET would thus correspond to the modified energy E.

A very important concept, but one which is by no means universally true, is the *effective LET*. The effective LET applies for those soft error mechanisms where the device susceptibility depends, in reality, on the charge deposited within a sensitive volume that is thin like a wafer. By equating the charge deposited at normal incidence to that deposited by an ion with incident angle θ, we obtain:

$$\text{LET(effective)} = \text{LET(normal)}/\cos\theta \quad \theta < 60°$$

Because of this relationship, one can sometimes test with a single ion at two different angles to correspond to two different (effective) LETs. Note that the effective LET at high angles may not be a realistic measure (see also 5.6). Note also that the above relationship breaks down when the lateral dimensions of the sensitive volume are comparable to its depth, as is the case with VLSI and other modern high density ICs.

2.1.6 *single event burnout*—SEB may occur as a result of a single ion strike. Here a power transistor sustains a high drain-source current condition, that usually culminates in device destruction. Sometimes known as SEBO.

2.1.7 *single event effects*—SEE is a term used earlier to describe many of the effects now included in the term SEP.

2.1.8 *single event gage rupture*— SEGR may occur as a result of a single ion strike. Here a power transistor sustains a high gate current as a result of damage of the gate oxide. Sometimes known as SEGD.

2.1.9 *single event functionality interrupt*—SEFI may occur as a result of a single ion striking a special device node, used for an electrical functionality test.

2.1.10 *single event hard fault*—often called hard error, is a permanent, unalterable change of state that is typically associated with permanent damage to one or more of the materials comprising the affected device.

2.1.11 *single event latchup* —SEL is an abnormal low impedance, high-current density state induced in an integrated circuit that embodies a parsitic pnpn structure operating as a silicon controlled rectifier.

2.1.12 *single event phenomena*—SEP is the broad category of all semiconductor device responses to a single hit from an energetic particle. This term would also include effects induced by neutrons and protons, as well as the response of power transistors—categories not included in this guide.

2.1.13 *SEP cross section*—is a derived quantity equal to the number of SEP events per unit fluence.

2.1.13.1 *Discussion*—For those situations that meet the criteria described for usage of an effective LET (see 2.1.5), the SEP cross section can be extended to include beams impinging at an oblique angle as follows:

$$\sigma = \frac{\text{number of upsets}}{\text{fluence} \times \cos\theta}$$

where θ = angle of the beam with respect to the perpendicularity to the chip. The cross section may have units such as cm^2/device or cm^2/bit or μm^2/bit. In the limit of high LET (which depends on the particular device), the SEP cross section will have an area equal to the sensitive area of the device (with the boundaries extended to allow for possible diffusion of charge from an adjacent ion strike). If any ion causes multiple upsets per strike, the SEP cross section will be proportionally higher. If the thin region waferlike assumption for the shape of the sensitive volume does not apply, then the SEP cross section data become a complicated function of incident ion angle. As a general rule, high angle tests are to be avoided when a normal incident ion of the same LET is available.

A limiting or asymptotic cross section is sometimes measured at high LET whenever all particles impinging on a sensitive area of the device cause upset. One can establish this value if two measurements, having a different high LET, exhibit the same cross sections.

2.1.14 *single event transients, (SET)*—SET's are SE-caused electrical transients that are propagated to the outputs of combinational logic IC's. Depending upon system application of these combinational logic IC's, SET's can cause system SEU.

2.1.15 *single event upset, (SEU)*—comprise soft upsets and hard faults. Latchup and burn-out are examples of the broader category of SEP.

2.1.16 *soft upset*— a soft upset is the change of state of a single latched logic state from one to zero, or vice versa. The upset is ″soft" if the latch can be rewritten and behave normally thereafter.

2.1.17 *threshold LET*—for a given device, the threshold LET is defined as the minimum LET that a particle must have to cause a SEU at $\theta = 0$ for a specified fluence (for example, 10^6 ions/cm^2). In some of the literature, the threshold LET is also sometimes defined as that LET value where the cross section is some fraction of the ″limiting" cross section, but this definition is not endorsed herein.

2.2 *Acronyms:*Acronyms:

2.2.1 *ALS*—advanced low power Schottky.

2.2.2 *CMOS*—complementary metal oxide semiconductor device.

2.2.3 *FET*—field effect transistor.

2.2.4 *IC*—integrated circuit.

2.2.5 *NMOS*—*n*-type-channel metal oxide semiconductor device.

2.2.6 *PMOS*—*p*-type-channel metal oxide semiconductor device.

2.2.7 *PROM*—programmable read only memory.

2.2.8 *RAM*—random access memory.

3. Summary of Guide

3.1 A SEP test consists of irradiation of a device with a prescribed heavy ion beam of known energy and flux in such a way that the number of single event upsets or other phenomena can be detected as a function of the beam fluence (particles/cm^2). For the case where latchup is observed, a series of measurements is required in which the fluence is recorded at which latchup occurs, in order to obtain an average fluence.

3.2 The beam LET, equivalent to the ion's stopping power, dE/dx, (energy/distance), is a fundamental measurement variable. A full device characterization requires irradiation with beams of several different LETs that in turn requires changing the ion species, energy, or, in some cases, angle of incidence with respect to the chip surface.

3.3 The final useful end product is a plot of the upset rate or cross section as a function of the beam LET or, equivalently, a plot of the average fluence to cause upset as a function of beam LET. These comments presume that LET, independent of Z, is a determinant of SE vulnerability. In cases where charge density (or charge density and total charge) per unit distance determine device response to SEs, results provided solely in terms of LET may be incomplete or inaccurate, or both.

3.4 *Test Conditions and Restrictions* —Because many factors enter into the effects of radiation on the device, parties to the test should establish and record the test conditions to ensure test validity and to facilitate comparison with data obtained by other experimenters testing the same type of device. Important factors which must be considered are:

3.4.1 *Device Appraisal*— A review of existing device data to establish basic test procedures and limits (see 7.1),

3.4.2 *Radiation Source*— The type and characteristics of the heavy ion source to be used (see 6.1),

3.4.3 *Operating Conditions*—The description of the testing procedure, electrical biases, input vectors, temperature range, current-limiting conditions, clocking rates, reset conditions, etc., must be established (see Sections 5, 6, and 7),

3.4.4 *Experimental Set-Up*—The physical arrangement of the accelerator beam, dosimetry electronics, test device, vacuum chamber, cabling and any other mechanical or electrical elements of the test (see Section 6),

3.4.5 *Upset Detection*— The basis for establishing upset must be defined (for example, by comparison of the test device response with some reference states, or by comparison of post-irradiation bit patterns with the pre-irradiation pattern, and the like (see 6.4)). Tests of heavy ion induced transients require special techniques whose extent depends on the objectives and resources of the experimenter,

3.4.6 *Dosimetry*—The techniques to be used to measure ion beam fluxes and fluence. Accelerator flux and fluence measurement techniques differ from those used for measuring the dose deposited by radioactive sources (see 6.5.4),

3.4.7 *Flux Range*—The range of heavy ion fluxes (both average and instantaneous) must be established in order to provide proper dosimetry and ensure the absence of collective effects on device response. For heavy ion SEP tests a normal flux range will be 10^2 to 10^5 ions/cm^2-s. However, higher fluxes are acceptable if it can be established that dosimetry and tester limits, coincident upset effects, device heating, and the like, are properly accounted for. Such higher limits may be needed for testing future smaller geometry parts.

3.4.8 *Particle Fluence Levels*—The minimum fluence is that fluence required to establish that an observance of no upsets corresponds to an acceptable upper bound on the upset cross section with a given confidence. Sufficient fluence should be provided to also ensure that the measured number of upset events provides an upset cross section whose magnitude lies within acceptable error limits (see 7.2.7.2). In practice, a fluence of 10^7 ions/cm^2 will often meet these requirements, and

3.4.9 *Accumulated Total Dose*—The total accumulated dose shall be recorded for each device. However, it should be noted that the average dose actually represents a few heavy ion tracks, <10 nm in diameter, in each charge collection region, so this dose may affect the device physics differently than a uniform (for example, gamma) dose deposition. In particular, it is sometimes observed that accumulated dose delivered by heavy ions is less damaging than that delivered with uniform dose deposition.

3.4.10 *Range of Ions*— The range or penetration depth of the energetic ions is an important consideration. The main problem with fission sources, such as Cf-252, is that their energy and range are so limited that incorrect data is often obtained. An adequate range is especially crucial in detecting latchup, because the relevant junction is often buried deep below the active chip. Power transistors are another category of device that are too thick to tolerate fission source ions. Some test requirements specify an ion range of >30 µm. The U.C. Berkeley 88-inch cyclotron and the Brookhaven National Laboratory Van de Graaff have adequate energy for most ions, but not all. Gold data at BNL is frequently too limited in range to give consistent results when compared to nearby ions of the periodic table. New medium-energy sources, such as the K500 cyclotron at Texas A & M and the TASCC cyclotron at Chalk River, Canada, easily satisfy all range requirements. High-energy machines that simulate cosmic ray energies, such as GANIL (Caen, France) and the cyclotron at Darmstadt, Germany, provide ranges that permit the tester to irradiate undelidded parts from any angle, including the back, in the presence of air.

4. Significance and Use

4.1 Many modern integrated circuits, power transistors, and other devices experience SEP when exposed to cosmic rays in interplanetary space, in satellite orbits or during a short passage through trapped radiation belts. It is essential to be able to predict the SEU rate for a specific environment in order to establish proper techniques to counter the effects of such upsets in proposed systems. As the technology moves toward higher density ICs, the problem is likely to become even more acute.

4.2 This guide is intended to assist experimenters in performing ground tests to yield data enabling SEP predictions to be made.

5. Interferences

5.1 There are several factors which need to be considered in accommodating interferences affecting the test. Each is described herein.

5.2 *Ion Beam Pile-up*— When an accelerator is being chosen to perform a SEU test, the machine duty cycle needs to be considered. In general, the instantaneous pulsed flux arriving at the DUT or scintillation is higher than the average measured flux, and the increase is given by the inverse of the duty cycle. A calculation should be made to ensure that no more than one particle is depositing charge in the DUT or scintillator at the same time. (The time span defining the "same time" is determined by the rate at which DUT elements are reset or at which the scintillator saturates.)

5.3 *Radiation Damage*:

5.3.1 A history of previous total dose irradiations for the DUTs must be known to assist in the determination of whether prior total ionizing dose has affected the SEU response.

5.3.2 During a test, the usual fluence for heavy ion tests (10^6 to 10^7 ions/cm^2) corresponds to kilorad dose levels in the parts. Total dose accumulated during the test shall be recorded, because the radiation effects of the accumulated dose may alter the SEU effect being monitored.

5.3.3 Sustained tests over a long period of time may lead to permanent degradation of electronics components, computers, sockets, etc. Fixtures must be checked regularly for signs of radiation damage, such as high leakage currents.

5.4 *Temperature*— Latchup susceptibility and soft error cross sections increase with temperature. In addition there are special situations in which SEP susceptibility will be particularly sensitive to temperature (for example, from the temperature dependence of feedback resistors).

5.5 *Electrical Noise*:

5.5.1 *Generalized Noise*—Because of the amount of electrical noise present in the vicinity of an accelerator, careful noise reduction techniques are mandatory. Cable lengths should be as short as possible, consistent with constraints imposed by the accelerator facility lay-out.

5.5.2 The tester must interact with accelerator personnel to ensure that the accelerator power supply is free of on-line instabilities that may affect the alignment and uniformity of the beam.

5.6 *Background Radiation*—Radioactivity induced by the heavy ion tests is minimal. The tester should perform radioactivity checks of the DUT board and parts after sustained runs; however, in general, DUTs may be safety packed and transported without delay after test.

5.7 *Ion Interaction Effects*:

5.7.1 The calculation of an effective LET (see discussion in 2.1.5) hinges on the thin slab approximation of the sensitive volume, which is less likely to hold for high density, small geometry devices. This problem can be examined by investigating the device SEP response to two different ions having the same effective LET.

5.7.2 The proportion of length to width of the sensitive volume is also assumed equal to one. Rotating the device along both axes of symmetry during the test may provide a more meaningful characterization.

5.7.3 As geometries continue to scale down, the possibility of multiple bit upsets increases. Hence, the nature of the ion's radial energy deposition becomes more important and it becomes more likely that two different ions of equivalent LET do not in fact have an equal SEP effect. In addition, the effects of irradiating at an angle become much more complex when an ion track overlaps two cells. The frequency of such overlapping upsets likewise depends on the track's radial energy deposition.

5.7.4 Another assumption is that the ion's energy deposition is in equilibrium at the device sensitive volume after the ion strikes the device. This may not always be the case with a top surface irradiation. One can investigate this possibility by irradiating the back of the device with highly energetic ions of adequate range. In the latter case, it is known that the ions' energy deposition will be in equilibrium when the ion reaches the sensitive volumes located near the surface.

5.7.5 Use of ions having adequate range is also important. Lower energy heavy ions lose LET as they slow down by attaching electrons and also show a contraction in the width of the radial energy deposition.

6. Apparatus and Radiation Sources

6.1 *Particle Radiation Sources* —The choice of radiation sources is important. Hence source selection guidelines are given here. A test covering the full range of LET values (both high and low Z ions) will require an accelerator. Cost, availability, lead times, and ion/energy capabilities are all important considerations in selecting a facility for a given test. Five source types are commonly used for conducting SEP experiments, each of which has specific advantages and disadvantages. The selection of a proper source that meets the test objectives in a cost-effective manner depends on test objectives and device appraisal (see 7.1.).

6.1.1 The five source types used for heavy ion SEP measurement are as follows:

6.1.1.1 *Cyclotrons*—Cyclotrons provide the greatest flexibility of test options because they can supply a number of different ions (including alpha particles) at a finite number of different energies. The maximum available ion energy of the heavy ion machines is usually greater than the energy (~2 MeV/nucleon) corresponding to the maximum LET. Hence, the ions can be selected to have adequate penetration (range) in the device. The main disadvantages of cyclotrons are the expense and occasional long down times.

6.1.1.2 *Van de Graaff Accelerators* —These accelerators have the important advantage of being able to pinpoint low LET thresholds of sensitive devices where lower energy, lower Z ions of continuously variable energies are desirable. These machines also offer a rapid change of ion species and are somewhat less expensive to operate than cyclotrons. However, because van de Graaff machines have limited energy, it may not be possible to obtain higher Z particles having an adequate range in some machines.

6.1.1.3 *Fission Sources*— The use of fissionable material, such as Californium-252, for SEP testing is presently in the advanced developmental stage. Researchers have shown that the spectrum of Cf-252 fission products has an average LET of ~45 MeV/(mg/cm ^{2}). These LET values are more likely to induce SEU than the heaviest ions prevalent in space. Attempts have been made to reduce the LET by interposing material (such as air) to degrade the beam energy, with some success; but it is clear that the range of these degraded energy ions is too short to extend the LET measurements below ~20 MeV/(mg/cm^2). The limited ion range may also preclude testing of devices where the sensitive region is not close to the surface, which may be true in some bipolar devices, or when attempting to induce latchup at a deep-lying *p*-well/epi junction.

6.1.1.4 *Alpha Emitters*— Naturally occurring radioactive alpha emitters provide a source for screening parts that are very sensitive to SEU. Some alpha emitters (for example, americium) emit particles with a single energy so that they can be used for establishing a precise LET threshold (of the order of <1 MeV/(mg/cm^2)).

6.2 *Test Instrumentation*—The test instrumentation can be divided into two categories: (*1*) Beam delivery, characterization and dosimetry, and (*2*) Device tester (input stimulus generator and response recorder) designed to accommodate the specified devices. The details of item (*1*) above are spelled out in 6.5.4, 6.5.5 and 6.5.6. The details of item (*2*) cannot be spelled out, but test philosophy and logic is sketched in 6.4. For information on various test instrumentation systems refer to Nichols.[2]

6.3 *Test Boards*— The DUTs will be placed on a board, usually within a vacuum chamber, during the test. To reduce the number of vacuum pump downs that will be required, it is highly desirable to include sockets in the boards for several devices. The board must be remotely positionable to change from one DUT under test to another, and rotatable to permit the beam to strike the DUT at oblique angles. Tester-to-DUT card cabling should be made compatible with the vacuum chamber bulkhead connectors to facilitate checkout prior to chamber installation.

6.4 *DUT Tester*:

6.4.1 There are many ways to design a tester/counter to measure soft errors, with special features best suited to a specified test application. However, there are certain general desirable features which any tester design should incorporate, and these will be addressed briefly.

6.4.2 Except in the simplest of special cases where a dedicated hardware tester is most desirable, the tests are performed by a computer, which exercises the DUTs directly, or alternatively makes use of an auxilliary "exerciser" or pattern operator. A tester whose design is based on the first approach, can be said to be "Computer Dominated," while the second type of design has been termed "Computer Assisted." Regardless of the test approach, the tester must be able to carry out the following operations:

6.4.2.1 Device initialization and functionality check,

6.4.2.2 Device operation while under irradiation,

6.4.2.3 Error detection and logging,

6.4.2.4 Diagnostic display in real or near-real time, and

6.4.2.5 Data processing, storage and retrieval for display.

6.4.3 While an effectively infinite variety of testers can be built to function adequately in any given set of circumstances, every tester, in addition to performing the operations listed above, should possess most of the following characteristics:

6.4.3.1 Adaptability to many device types. This generally implies software control with programs written in a high-level language,

6.4.3.2 Well-defined duty factor (ratio of device "live" time to total elapsed time). Without a knowledge of the duty factor, device vulnerability cannot be quantified,

6.4.3.3 Speed of operation and high duty factor. This is especially important when tests are performed in a high particle flux. Generally, a computer-assisted tester design is implied by this characteristic,

6.4.3.4 Real-time diagnostic data display capability. Mandatory for immediate detection of anomalous test conditions and data, and

6.4.3.5 Capability for some data reduction while tests are in progress. Desirable for optimization of test procedures while data are being acquired.

6.4.4 In summary, a tester will usually be of the computer-dominated or computer-assisted type. It should be programmable to accommodate a variety of device types with a minimum need for new, specialized hardware interfaces and minimum time required for reprogramming. The tester design should be sufficiently flexible to meet the changing requirements of new device technologies. Finally, the experimenter must understand the extent to which the device is being tested (its fault coverage) in order to arrive at a quantitative result. He must know what fraction of the time the device is in a SEP-susceptible mode and also what fraction of the chip's susceptible elements are omitted from testing altogether. Complex devices do not always permit easy testing access. In

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[2] Nichols, D. K., et al, "Trends in Parts Susceptibility to Single Event Upset From Heavy Ions," *IEEE Transactions on Nuclear Science*, Vol NS-32, No. 6, December, 1985, p. 4187. (See updated addition by D. K. Nichols et al in *IEEE Transactions on Nuclear Science*, Vol NS-34, No. 6, December, 1987, p. 1332, Vol NS-36, December, 1989, p. 2388, Vol NS-38, December, 1991, p. 1529, *IEEE Radiation Effects Data Workshop*, December, 1993, p. 1).

such cases, a thorough understanding of the untested elements must be obtained to permit extrapolation from data obtained by the test.

6.5 *A Typical Cyclotron Test Set-Up* :

6.5.1 *Schematic*—A schematic overview of a typical SEP test set-up is provided in Fig. 1. The essential features are a collimated, spatially uniform beam of particles entering a vacuum chamber which may be located in an area remote (for example, behind shielded walls) from the tester/counter and dosimetry electronics. Test boards, shutters, and beam diagnostic detectors are in, or near, the vacuum chamber.

6.5.2 *Vacuum Chamber*— A typical vacuum chamber interior is shown in Fig. 2. The essential features are the beam collimators/shutters and sensors, and a rotatable and translatable board for positioning the selected DUT at the selected angle in the beam. Dosimetry may or may not be located in the vacuum chamber.

6.5.3 *DUT Board*—A typical board showing sockets for several DUTs is shown in Fig. 3, together with the associated driver logic. A device located outside the beam can be used as a reference device or sometimes one-half of a test device can be used to compare with the other half when the likelihood of both sides being hit at the same time is low. The round hole permits passage of the beam to the downstream silicon surface barrier (SSB) detectors located at the rear of the chamber interior. The horizontal hole in the test frame is an opening to a SSB detector that may be used to check beam uniformity along the vertical axis.

6.5.4 *Beam Dosimetry System*:

6.5.4.1 The flux and fluence of the selected heavy ion beam may be measured by passing it through a scintillator. The beam may pass through a very thin (microns) foil whose thickness is chosen to give the proper light amplitude to correspond with the beam's LET. An alternate method is to insert an annular scintillator into the beam which admits part of the beam unimpeded onto the DUT while the outer portion is stopped by a thick scintillator. The light is then piped to a photomultiplier tube (PMT) and counted as shown in Fig. 4. Trends are for the source facility to provide the dosimetry.

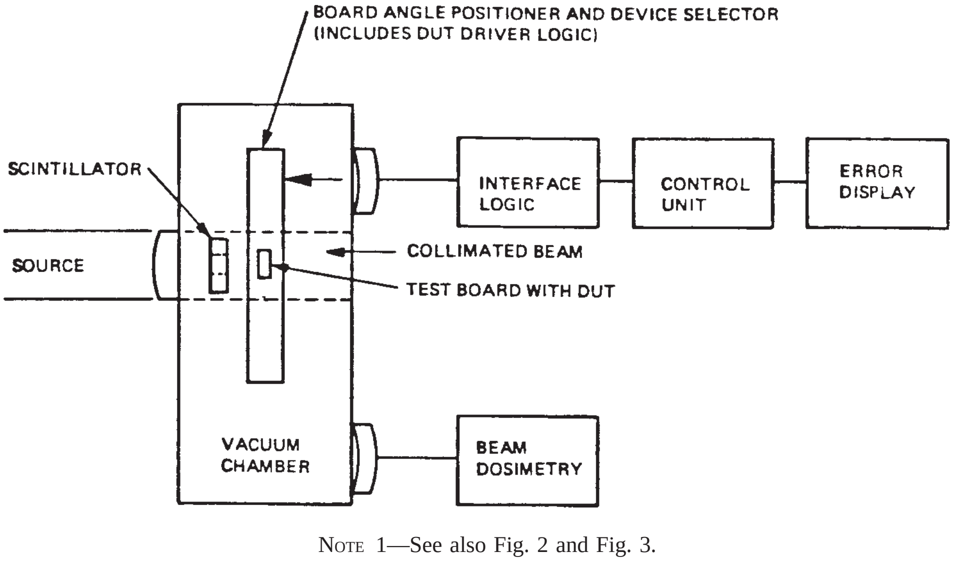
6.5.4.2 The bias applied to the PMT will be increased gradually until pulses are of adequate amplitude to permit discriminator adjustment. The discriminator must reject all noise pulses and pass all pulses caused by the beam particles. The beam intensity (flux) should be kept low enough to avoid pulse pile-up in the dosimetry electronics. Otherwise a measurement of the single pulse length and a calculation of the pile-up effect on the counter readout are required.

6.5.5 *Uniformity Measurement System* —Beam uniformity will first be established in a gross manner by suitable accelerator adjustments leading to a visibly uniform beam displayed on a quartz plate inside the beam tube when the accelerator is run at high fluxes. After the intensity has been reduced (usually by several orders of magnitude), the uniformity can be rapidly checked in several ways: (1) Radial uniformity by comparing beam count in two concentric circles of different areas (scintillator area versus area of solid state detector at rear), (2) Uniformity obtained by vertical motion of DUT board frame to which a horizontally mounted, position-sensitive detector is affixed, and (3) Measurement at selected points around the beam circumference. In general a 10 % variation in beam readings is deemed acceptable.

6.5.6 *Beam Energy Measurement System* —The system, shown in Fig. 5, consists of a bias supply, test pulser, surface barrier detector with collimator, preamplifier, spectroscopy amplifier, multichannel analyzer (MCA), and the radioactive calibration source. Calibration of the system is performed, using a radioactive source of known alpha particle energy. The energy spectrum can be displayed on a MCA screen. Some degradation in energy occurs between the reported energy at the source and at the DUT.

6.6 *High Energy Machine Features* :

6.6.1 A high energy machine provides energies of several GeV per atomic mass unit more characteristic of cosmic ray energies than other sources. This fact affords simplification in some aspects of testing. There may be no need to use a vacuum chamber nor



NOTE 1—See also Fig. 2 and Fig. 3.

FIG. 1 Schematic Overview of SEU Test

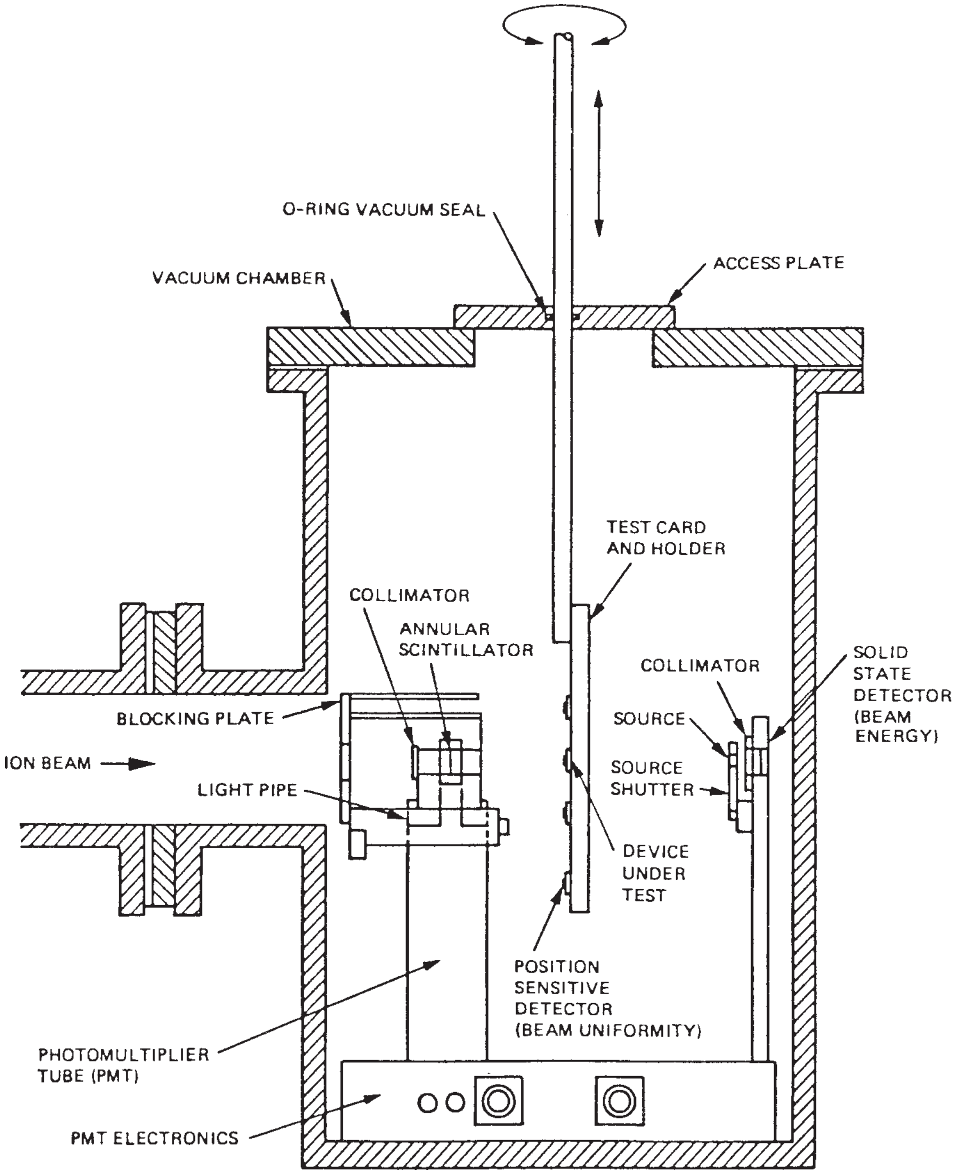


FIG. 2 Typical Vacuum Chamber

to remove lids from the devices, since beam energies are adequate to penetrate through air and the whole device structure. High energy machines may have special beams and dosimetry problems, and are unlikely to provide the same flexibility as low energy machines for changing ions and energies.

7. Procedure

7.1 *Device Appraisal*:

7.1.1 The first step is to estimate the device SEP susceptibility by surveying existing data. From this data survey, or from information obtained from modeling studies, it may be possible to obtain an estimate of the LET (linear energy transfer) threshold for the devices to be tested. Such information can assist in the selection of ion species (and energy) with which to begin the test runs, using published values for LET for ions of various energies. Much of the SEP device test data has been published in the open literature,[2] but communication with the leading SEP experimenters[3] is a useful step.

7.1.2 To estimate the LET threshold for a given device one can use the following approach. First look for data for devices having a similar function, technology and similar feature sizes (transistor density), irrespective of the manufacturer. If alpha particle data is available, any observed upsets would indicate a very sensitive device (see Note 1), with a threshold LET ≤ 1 MeV/(mg/cm^2). If proton data is available, any upsets also show a sensitive device, probably with an LET threshold ≤ 6 MeV/(mg/cm^2). Any heavy

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[3] Sections on Single Event Phenomena, *IEEE Transactions on Nuclear Science*, all December issues dating from 1979.

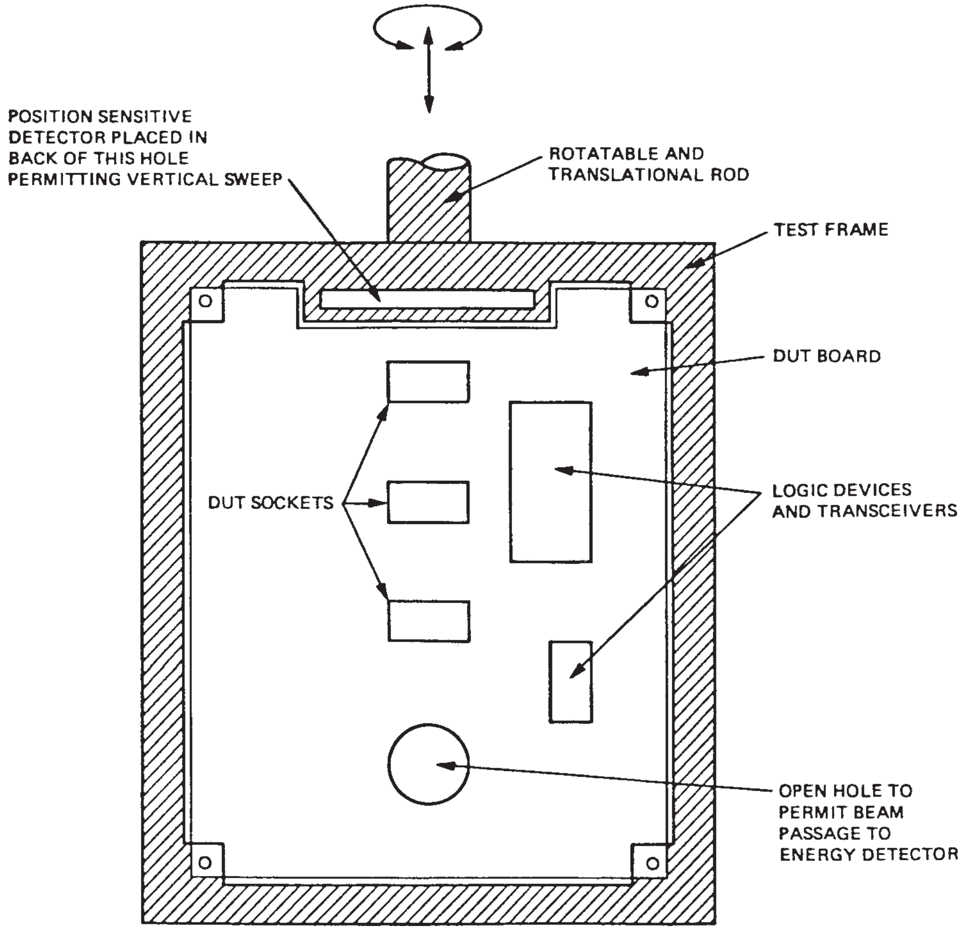

FIG. 3 Typical DUT Board (Front Face) Located in Vacuum Chamber (Connector Cables Lead Off from Rear of Board)

ion data available also provides a very crude estimate of what might be expected for the device to be tested. If no data is available, one should assume that certain technologies and functions have a high risk for upset. For silicon devices, a rough division is given as follows:

HIGH RISK DEVICES:
1) Bipolar RAMs
2) Low power logic (54Lxxx)
3) LS and ALS (low power Schottky) logic
4) Microprocessors and bit-slices
5) NMOS, PMOS technology
6) Dynamic RAMs

LOWER RISK DEVICES:
1) Some CMOS bulk devices (except for possible latchup)
2) Some CMOS/SOS technology
3) Standard power logic
4) PROMs
5) Low speed devices
6) Devices having large feature sizes (≥10 µm)

NOTE 1—Some manufacturers test their devices with an alpha particle source to determine whether radioactive contaminants in the package are capable of causing upset. If they see upsets and solve the problem by application of barrier materials, such as polyamides or silicon nitride, to stop radioactive alphas, they do not succeed in preventing upsets from much more energetic cosmic ray alpha particles.

7.2 *Pre-Test Procedures*—Parties to the test must first establish the test circumstances. As a minimum, establish the items specified in 3.4. For the case where two or more organizations are involved, define and agree to detailed interface conditions. Consider all the possible conditions and interferences of Section 5. Additional pretest procedures include: preparation of a test plan, device preparation, tester checkout, dosimetry checkout, installation and alignment of equipment, provision for latchup monitoring capability, and particle-beam tuning procedures.

7.2.1 *Test Plan Preparation*—Prepare a test plan to serve as a guide during testing. The plan shall include:

7.2.1.1 Scope of test,

7.2.1.2 Overall test objectives,

7.2.1.3 Specific parts test objectives (including priorities),

7.2.1.4 Test schedule (including description of ion beams),

7.2.1.5 Personnel schedule,

7.2.1.6 Logistics,

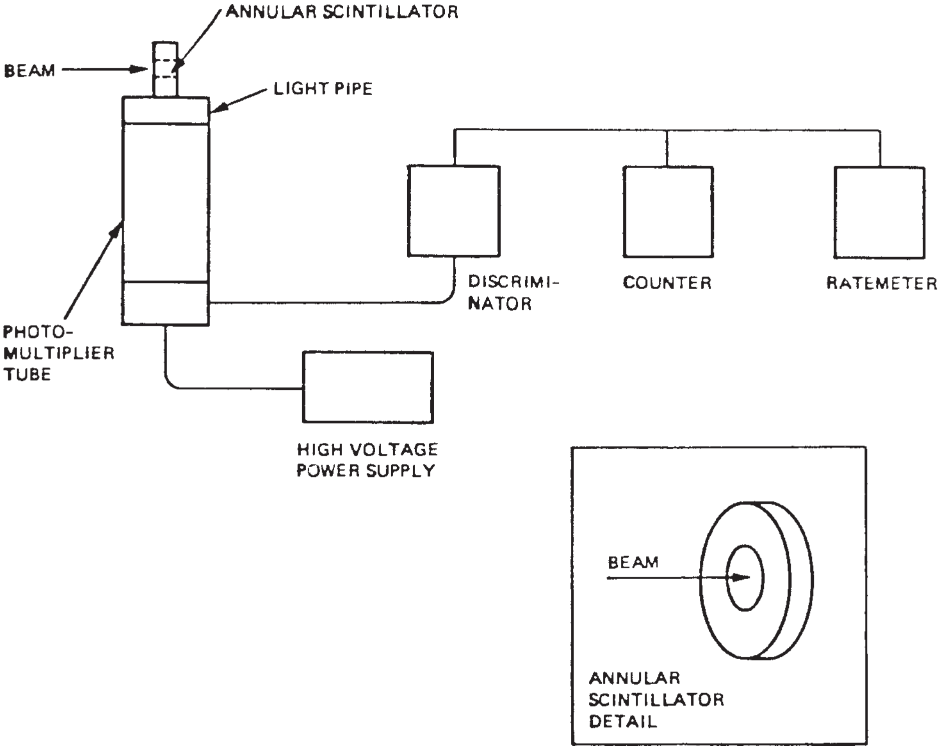

FIG. 4 A Beam Measurement System

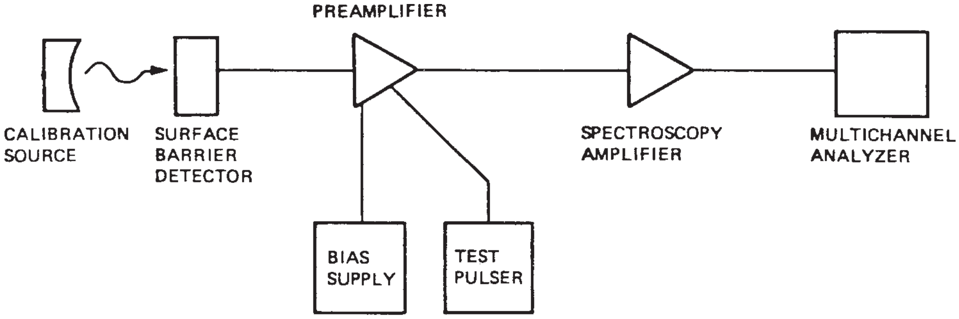

FIG. 5 An Energy Measurement System

7.2.1.7 Data sheet format (see also Section 8), and

7.2.1.8 Special conditions.

7.2.2 *Device Preparation*—Except for very high energy testing, all devices must be without lids to permit access of the heavy ion beam to the chip face. If special barrier materials (for example, polyamides, and the like) have been used to coat the chip, they must also be removed. Use manufacturer's recommended procedure when known. Because lid removal may damage devices, one must subject the devices to a follow-on functional test. Take care to order the proper package type for use in the test card, and avoid ceramic packages because they are difficult to delid. Flatpacks need special holders with a hole in the lid to permit direct exposure of the chip to the beam. Position devices in such a way as to allow the largest possible incident beam angles with respect to the surface normal.

7.2.3 *Tester Check-Out*— Perform a device tester "dry-run" with the DUT in place prior to the test. It is strongly recommended that this checkout be performed with all equipment that will actually be used on-site, including the long cables that are required to connect the DUT to the instrumentation outside of the irradiation area. For some parts, a useful way to simulate SEUs is to illuminate the DUT with a high intensity strobe light. This verifies that the hardware (but not the software) works correctly. Also, make available the strobe for checkout of the on-site installation.

7.2.4 *Dosimetry Checkout*—Close coordination between the user and the accelerator facility operators is required to ensure proper real-time fluxes. For the low fluxes used in SEP experiments, it is highly probable that special dosimetry, such as described in 6.5.4, will be required.

7.2.5 *Installation and Alignment of Equipment*—Connect the vacuum chamber with the evacuated beam pipe of the accelerator. Accomplish alignment of the equipment visually through a port in the vacuum chamber; however, a laser source provides a faster and more accurate method.

7.2.6 *Latchup Monitoring Capability* —A substantial current transient (equal to several times the operating current) is a positive indication of incipient latchup. The testing constraints shall determine the level of precaution necessary to protect the test device, or to obtain engineering data such as sustaining current or current levels for catastrophic failure.

7.2.7 *Particle Beam Tuning Procedures* —Particle beam preparation can be a long process that may require close interaction between the facility operator and the user. The identity of ion species and energy delivered by a Van de Graaff accelerator or a cyclotron must never be taken for granted; the first priority of the user is to verify the ion species and energy. Because of the unusually low flux levels for SEU testing, the user will need to monitor the flux intensity and beam uniformity outputs and provide this information to the facility operator to make necessary beam adjustments.

7.2.7.1 *Energy Measurement*—The energy measurement system must have adequate resolution to determine the beam energy and, in some cases, the proper elemental ion selection. In general, however, the LET variation with beam energy is rather small, so strict requirements on the energy (or energy spread) may not be warranted. (See 6.5.4 for discussion of possible ion detectors.) Calibrate the energy-measurement system using a radioactive source. After the beam flux has been lowered sufficiently to avoid pileup in the detector(s), an energy spectrum is accumulated and displayed on a multichannel analyzer (MCA) (Fig. 5). The MCA display indicates if any scattered beam is present and the peak energy indicates whether or not the desired ion species is present. Any presence of undesired species is usually due to mistuning of the accelerator, bending magnets, (or improper selection of ion species—charge state, mass, and energy), and must be corrected by the facility operator.

7.2.7.2 *Flux Measurement*— The fluxes required for heavy ion testing usually range between 10^2 to 10^5 ions/cm^2-s. These ranges are lower than most standard monitoring equipment at accelerator facilities is capable of measuring. Hence, special measuring techniques are required. It is convenient to establish a method for counting each individual ion in the beam, using a collimator, scintillator, light pipe, photomultiplier (PMT), counters, and a rate meter (see Fig. 4). It is necessary to adjust the discriminator voltage to count each ion while rejecting background noise. An annular scintillator system precludes beam energy degradation by allowing those particles that hit the device to pass through a hole. Those particles stopped in the scintillator are counted to determine the flux.

7.2.7.3 *Beam Uniformity Measurement* —After the proper ion species and energy have been obtained, measure and adjust the beam-spot uniformity, if necessary. Make adjustments using beam defocusing techniques, or thin scattering foils, or both, to diffuse the beam. At high fluxes, the beam uniformity is most easily adjusted by visually observing the beam on a fluorescing material (such as quartz) that can be inserted in the beam pipe near the vacuum chamber. The subsequent uniformity measurements taken at attenuated fluxes with detectors should be accurate enough to ensure that the fluence (ions/cm^2) counted by the measurement system scintillator is within a few percent of the fluence impinging on the DUT. If the DUT is placed behind a hole in the annular dosimetry scintillator, a particle counter in line with the DUT position can be used to compare the fluence at the DUT position with that measured by the dosimetry scintillator. The energy measurement detector, operated in a particle counting mode, can be used for this purpose. For applications where the threshold LET is the primary quantity to be measured, these conditions on uniformity can be relaxed. However, any cross section data thereby becomes less accurate and less valuable to other users.

7.2.7.4 *Beam Selection*— The range of ion species that will be used to test a given DUT is determined by the LET threshold of the device. Heavier ions produce larger LET and are usually used first to test a given device. Take care to ensure that the range of a given ion is large compared to the thickness of the device overlayers to ensure that the beam LET is nearly constant while the ion traverses the DUT. The ion species and energy chosen to test a given set of devices should be one that the accelerator operators have produced before. Using an ion beam (species and energy) that has not been produced before can be very time consuming. To facilitate rapid ion beam change, two or more ion beams with nearly identical rigidity (bending in a magnetic field) can be chosen. Take care to ensure that the beams with the smaller LET are not contaminated with the beam having a higher LET. Standard nuclear instrumentation for single particle energy measurement can easily measure parasite beam contamination to better than one part per million. In general, changes of the following beam conditions can be made according to the ranking given in order of increasing difficulty:

(1) Change flux (easily changed within certain limits),

(2) Correct beam uniformity,

(3) Change beam energy (specified discrete energy increments in a cyclotron; continuous in an electrostatic accelerator),

(4) Change to a new ion species (some ions are easier to obtain than others).

7.3 *Test Implementation*:

7.3.1 *General Discussion*:

7.3.1.1 The end goal is to obtain a plot of the SEP cross section versus LET with sufficient data points to establish the value of the constant high LET cross section as well as the LET value (threshold) where this cross section vanishes.

7.3.1.2 A test plan, prepared before testing, will serve as a guide for the procedures and decisions to be made on-the-run during the actual irradiation period. However, no test plan can be followed slavishly, because accelerator variables and the results of previous data runs must be factored into later runs.

7.3.1.3 During the test, it is imperative to understand the implications of the data; including the LET and range of all particles at the beam energy being used, or available for use.

7.3.1.4 If the device does not upset in the initial run, there are several follow-on options available:

(1) Increase fluence;

(2) Change beam angle (see Note 2). Flips that occur with the beam only at oblique angles indicate that the device is near threshold;

(3) Change bias. A lower bias (minimum of the specified operating range) promotes bit-flips and a high bias (maximum specification) usually promotes latchup. If the onset of SEP occurs with a small bias change, then this fact indicates that the original conditions are close to that of the threshold LET;

(4) Change to another device of the same type;

(5) Change operating parameters, including initial load configuration;

(6) Change ion energy;

(7) Change ion species to obtain a higher LET.

NOTE 2—For very high energy sources, there is no limit on the angle because the beam energy can penetrate along the face of the chip (90° from perpendicular). For other accelerators, the maximum angle depends on the extent that surrounding material occludes the beam.

7.3.1.5 If the device upsets, there are also several options available for follow-on tests to complete the test program:

(1) Change flux to get a statistically meaningful number of upsets without overloading device tester or dosimetry;

(2) Change beam angle;

(3) Change operating parameters, including initial load configuration, clocking, and the like,

(4) Repeat runs to give a statistical measure, or to verify beam stability;

(5) Go to another part of the same device type to measure part-to-part variability;

(6) Change to another temperature (if applicable);

(7) Change ion energy to give a new LET. A lower LET would permit convergence on the threshold LET;

(8) Change ion species to introduce a new range of LET values for the beam.

7.3.2 *Monitoring for Latchup*—When establishing a device's susceptibility to latchup, make provisions to ensure that a current transient has occurred. Such transients can be *a priori* evidence of latchup, requiring that no demonstration of sustaining current be made. For reasons of design, sustaining current measurement may be desired. In such cases, use active circuit techniques to minimize part exposure to excessive current.

7.3.3 *Handling*—Special care must be taken in handling DUTs used for heavy ion tests because they have usually been delidded to permit penetration by the heavy ion beam into the active regions of the device. All parts must be handled according to the usual rules for parts susceptible to damage from electrostatic discharge.

7.3.4 *Parts Samples*— Device-to-device variability for soft errors is generally small for devices produced with the same masks and fabrication steps, so a test sample size can also be small. However, the system user must be sure that flight devices are truly equivalent to those tested, because manufacturers often make relevant process changes affecting SEP sensitivity without changing the device's numerical designation.

8. Report

8.1 *Test Data Sheet*— The test data sheet shall contain the following information:

8.1.1 Dates, times, names of test personnel,

8.1.2 Source type, name and location; beam ion and energy,

8.1.3 Part type, serial number, functional description, technology, manufacturer, date code and mask number if known,

8.1.4 Device duty factor and fractional portion of the chip tested if applicable. The number of flip-flops (bit elements) for each tester configuration should also be listed,

8.1.5 Reason for each test run; give changes from previous test run,

8.1.6 Device operating parameters (bias, clock frequency, temperatures, and the like),

8.1.7 Device test pattern or operational mode, including duty factor,

8.1.8 Beam angle,

8.1.9 Beam counts (related to fluence), run time,

8.1.10 Number of errors and special comments (anomalous incidents), and

8.1.11 When instrumented, a report of transient events.

8.2 *Final Report*— The test documentation shall consist of a final report that shall include the following information:

8.2.1 Introduction giving background and test objectives,

8.2.2 Complete device description, including date codes, and number of flip-flops (bit elements) per device,

8.2.3 Description of experimental set-up (including schematic) and methods. The description should also include accelerator beam characteristics, description of the device tester (exerciser), and documentation of the dosimetry system and procedures,

8.2.4 Descriptive interpretation of data (for example, threshold LET, a plot of cross sections as a function of LET),

8.2.5 Interpretation of data in terms of objectives (for example, SEU rate calculations, ranking of parts, and the like), and

8.2.6 Samples of data sheets or an appendix containing all data for the test.

9. Keywords

9.1 SEP cross section; single event; single event effect; single event phenomena; single event upset; space environment

APPENDIX

(Nonmandatory Information)

X1. DEVICE UPSET RATE PREDICTION

X1.1 The device upset rate is obtained by folding in the measured cross section (as a function of LET) with the appropriate environmental specification (heavy ion fluence versus LET). The cross section must span a range of LET that includes the lower limit on the LET required to induce upset (threshold LET) up to a high LET associated with iron or krypton. For the special case of interplanetary space, which includes geosynchronous satellite orbits, the environmental specification is known as the Heinrich integral. The Heinrich curve is a plot of the flux of ions having an LET equal to or greater than the LET value selected on one coordinate. It thus represents the sum of all ion species of all energies according to their known LET. The Heinrich integral should include variations relevant to the time of launch within the eleven-year solar cycle as well as parametric curves corresponding to the percentage of time in flight that the fluxes are exceeded by random high intensity solar flares. Similar curves have also been developed for satellite orbits (as a function of altitude and inclination) and aircraft routes (as a function of altitude and latitude).

X1.2 A computer code[4] is required to combine the experimental data for a given device with the omnidirectional flux (or fluence) appropriate to the environment. The procedure for calculating SEU rates for a given device or system is, however, beyond the scope of this guide. Here, we limit ourselves to establishing the experimental data for a given device under test (DUT) that is required for such a calculation.

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[4] Computer code, CRIER code, IRT, La Jolla, CA, UPSETRATE 1 and 2, Jet Propulsion Laboratory, (JPL), Pasadena, CA, CREME code, U.S. Naval Research Laboratory, Washington, DC, or equivalent, have been found suitable for this purpose.