JEDEC STANDARD

Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation

JESD57A

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TEST PROCEDURES FOR THE MEASUREMENT OF SINGLE-EVENT EFFECTS IN SEMICONDUCTOR DEVICES FROM HEAVY ION IRRADIATION

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Foreword

This standard establishes requirements for conducting a heavy-ion single-event effects (SEE) test in electronic devices. The standard can be referred to as a "Heavy Ion SEE Test Standard. An additional heavy-ion guideline document is ASTM 1192, and other documents that coincide are JESD234 and JESD89. In general all of these documents assist in electronics testing where deposited energy (and energy loss) can alter a device operation. The benefits of this revision are to capture and document several of the recently observed test considerations found in today’s advanced devices (see Annex D for more detail). The standard assures the user (1) of an approach for bounding an acceptable test for direct-ionization induced upset, (2) that consideration must be given to device overlayers, (3) of a discussion on the clarity between destructive and non-destructive events, (4) of an extended discussion on complex modes of failure, (5) that guidance is given for power MOSFET testing, and (6) that guidance is given to dataset analysis.

TEST PROCEDURES FOR THE MEASUREMENT OF SINGLE-EVENT EFFECTS IN SEMICONDUCTOR DEVICES FROM HEAVY ION IRRADIATION

(From JEDEC Board Ballot JCB-17-21, formulated under the cognizance of JC-13.4 Committee on Radiation Hardness: Assurance and Characterization.)

1 Scope

1.1 Purpose

This test method defines the requirements and procedures for single-event effects (SEE) testing of analog and/or digital discrete semiconductor devices and integrated circuits by irradiation with energetic heavy ions.

1.2 Applicable test facilities

This test method is valid only when using a Van de Graaff or cyclotron accelerator. In principle, this test method may be applicable to conduct SEE tests using a synchrotron accelerator; however, the application of this method to accelerators that deliver discontinuous (pulsed) flux and the potential interferences are not directly addressed in this test method. A test method for a Cf-252 source is also not included. This test method assumes that the accelerator test facilities can provide measurements of ion fluence and total ionizing dose, and that the testing organization has the equipment for performing these tests.

1.3 Basic effects addressed

SEE includes any manifestation of soft or hard errors induced by a single ion strike. These errors include single event upset (SEU) (comprising both single-bit upset (SBU) and multiple cell upset (MCU)), single-event functional interrupt (SEFI), digital and analog single-event transients (SET) that may introduce a soft error in nearby circuits, single-event burnout (SEB), single-event gate rupture (SEGR), and single-event latchup (SEL). Newer technologies can have undefined modes of SEE that will require measurement and analysis capabilities that are beyond the scope of this document.
See [1-3] for information on the SEE susceptibilities of different device types.

1.4 Limits of the test method

This test method only applies to SEE testing using heavy ions. Heavy ions are defined as ions with an atomic number $Z > 1$.

1.5 Goal of SEE testing

For SEU, SET, SEFI, and SEL, the end product of the test is a plot or table of the SEE cross section vs. linear energy transfer (LET). The amount of data required is detailed in clause 7. These data can usually be combined with the predicted heavy-ion environment of the intended space application in order to predict an expected SEE rate for the device under test (DUT). In addition, SET testing can result in characterization of transient duration and/or amplitude.

For SEB and SEGR, the end product is to establish safe operation limits. Protective-mode testing (see 5.2.4.3) can be employed to measure an SEB cross-section curve; there is no known SEGR protective-mode test circuit.

1 Scope (cont'd)

1.6 Warnings

These tests can involve hazardous materials, operations, and equipment.

- Many power devices require operating voltages in excess of 32 volts and safety precautions shall be followed to ensure safe operations of all equipment and personnel.
- Test hardware and parts may become radioactive.

This test method does not address all of the safety problems associated with this type of testing. It is the responsibility of the user of this test method in consultation with accelerator personnel to establish the appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

1.7 Interferences

Annex A must be reviewed before initiating SEE testing.

2 Normative References

The following normative documents contain provisions that, through reference in this text, constitute provisions of this standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies:

ASTM F 1192, *Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices*

MIL-STD-750, *Test Method 1080 Single Event Burnout and Single Event Gate Rupture*

ESA/SCC 25100, *Single Event Effects Test Method and Guidelines*

IEEE STD 300, *IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors*

JESD88, *JEDEC Dictionary of Terms for Solid-State Technology, 6th Edition*

MIL-PRF-38535, *Integrated Circuits (Microcircuits) Manufacturing, General Specification for*

MIL-HDBK-814, *Ionizing Dose and Neutron Hardness Assurance Guidelines for Microcircuits and Semiconductor Devices*

3 Terms and definitions

For the purpose of this standard, the terms and definitions given in JESD88 and the following apply:

Bragg curve: For a collimated beam of particles, the relationship between the average specific ionization (average linear energy transfer) and the residual range of the particles in a given material.

Bragg peak: The maximum in the Bragg curve that occurs just before the ion comes to rest in the material.

critical charge (Q_c): The minimum amount of collected charge that will result in a single-event effect (SEE).

cross section (σ): The number of events per unit fluence.

NOTE If the depth of the sensitive volume is small compared to its lateral dimensions, the SEE cross section (σ) can be calculated as follows:

$$\sigma = \text{number of events} / (\text{fluence} \times \cos(\theta))$$

where θ = angle of incidence of the ion with respect to normal incidence. The recommended cross-section units are cm^2/device or μm^2/bit. The saturated (or asymptotic) cross section will have an area equal to the sum of all the sensitive areas of the device, provided that one heavy ion induces one upset per strike on a sensitive region. If any ion causes multiple upsets, the cross section may be higher than the sum of the areas of the geometric structures.

DUT: Device under test.

effective LET (for particle radiation) [LET(*θ*)]: The linear energy transfer (LET) modified to account for the change in total energy transferred from an incident ion as it traverses a sensitive volume when the path of the ion is not normal to the irradiated surface of that volume (see also LET).

NOTE 1 The cosine dependence may be applicable for this modification. Caution must be used; see Annex A.

$$LET(\theta) = LET(0°) / \cos\theta$$

where θ is the angle of incidence of the ion with respect to normal incidence (i.e., the angle between the ion path and the normal at the point of incidence).

NOTE 2 The equation in note 1 is valid only when the depth of the sensitive volume is less than the other two dimensions in the rectangular parallelepiped (RPP) model (examples violating this shallow depth include older bipolar devices with very deep sensitive areas compared to the size of the epilayer tub, power devices, and newer SiGe products on bulk silicon).

fluence: The total number of ions incident on a surface during a given exposure, per unit area.

NOTE 1 The equation "fluence = *N/A*" applies, where *N* and *A* represent the quantities number of particles and area. Fluence can be calculated by integrating the flux density over the given period of time, e.g., a run.

NOTE 2 The unit symbol (e.g., cm^{-2}) does not identify particle type because there are no standardized unit symbols for "particle" and types of particles. The particle name may be placed before the term, e.g., "ion fluence", or in the spelled-out unit name, e.g., "ions per square centimeter".

NOTE 3 Fluence of particle radiation incident on a surface is maximized when the surface is normal (perpendicular) to the direction of the incident particle flow.

3 Terms and definitions (cont'd)

flux; flux density: The time rate of flow of ions per unit area incident on a surface.

NOTE 1 The equation "flux = $N/(A \cdot t)$" applies, where *N*, *A*, and *t* represent the quantities number of particles, area, and time.

NOTE 2 The unit symbol (e.g., $cm^{-2} \cdot s^{-1}$) does not identify particle type. The particle name may be placed before the term, e.g., "ion flux", or in the spelled-out unit name, e.g., "ions per square centimeter second".

NOTE 3 Flux is maximized when the surface is normal to the direction of the incident particle flow.

linear energy transfer (LET): The amount of energy per unit length deposited or transferred by an ion traversing a material, often expressed as $MeV \cdot cm^2/mg$.

NOTE LET is strictly defined in terms of energy divided by distance, e.g., MeV/cm, eV/nm, keV/µm. However, since the energy lost is directly proportional to the density of the material traversed, it is useful to divide the LET by the density of the material. For the purposes of this standard, this derived quantity (i.e., MeV/cm divided by mg/cm^3) is referred to as linear energy transfer (LET).

multiple-bit upset (MBU): A single event that induces upsets of multiple cells where two or more of the error bits occur in the same logical word (or frame for FPGAs).

NOTE An MBU is a logical manifestation of a single event.

multiple-cell upset (MCU): A single event that induces several cells (e.g. memory cells or flip-flops) in an integrated circuit to flip their state at one time.

NOTE 1 The error bits are usually, but not always, physically adjacent. This does not imply logical adjacency, since that will depend on how access to the cells are routed through the component.

NOTE 2 MCUs can manifest themselves logically as MBUs, multiple SBUs, or a combination of the two.

saturated cross section: The maximum observable cross section.

NOTE The saturated cross section appears as the asymptotic upper section of the cross section vs. linear-energy transfer (LET) curve. An additional increase in LET will not increase the cross section of the device. On some devices, the cross section may not reach saturation.

sensitive volume: A region or multiple regions within which enough charge is ionized to cause an SEE.

NOTE A sensitive volume is a construct associated with device interaction models needed for the prediction of a single-event error rate. The fundamental assumption for these models is that there is a sensitive region or collection of sensitive regions within a circuit element that can collect charge generated by the passage of a heavy ion [or particle].

single-event burnout (SEB): An event in which a single energetic-particle strike induces a localized high-current state in the device, resulting in catastrophic device failure or in permanent degradation that is usually characterized by a significant increase in leakage current that exceeds the manufacturer's maximum specification.

3 Terms and definitions (cont'd)

single-event effect (SEE): Any measurable or observable change in state or performance of a microelectronic device, component, subsystem, or system (digital or analog) resulting from the passage of a single energetic particle.

NOTE Single-event effects include single-event upset (SEU), single-bit upset (SBU), multiple-bit upset (MBU), multiple-cell upset (MCU), single-event functional interrupt (SEFI), single-event latch-up (SEL), single-event hard error (SHE), single-event transient (SET), single-event burnout (SEB), and single-event gate rupture (SEGR).

single-event functional interrupt (SEFI): A non-destructive interruption resulting from a single ion strike that causes the component to reset, hang, or enter a different operating condition or test mode.

NOTE 1 A SEFI is often associated with an SBU/MBU in a control bit or register.

NOTE 2 Changes in functionality may require a soft or hard reset of the device, reprogramming of the control registers, or power cycling.

NOTE 3 A SEFI can introduce a latent reliability issue due to a period of high current. SEFIs that result in permanent damage are designated as single-event hard errors.

single-event gate rupture (SEGR): An event in which a single energetic-particle strike results in a breakdown and subsequent conducting path through the gate oxide of a MOSFET, MOS capacitor, or floating-gate memory.

NOTE An SEGR is manifested by an increase in gate leakage current and can result in either the permanent degradation or the complete failure of the device.

SEGR post-irradiation gate stress (PIGS) test: An electrical test conducted after heavy-ion irradiation to verify the gate integrity.

NOTE Typically, the PIGS test is accomplished by applying the maximum specified gate-source voltage to the gate terminal and ensuring that the gate leakage current remains within the manufacturer's specification (this test may use either the specified positive or negative rated gate voltage or both conditions).

single-event hard error (SHE):

An irreversible change in operation that is typically associated with permanent damage to one or more elements of a circuit. Examples of radiation induced hard errors are single event gate rupture, single event burnout and destructive latch-up.

NOTE The error is "hard" because the component no longer functions properly, even after power reset and re-initialization.

single-event latchup (SEL): An abnormal high-current state in a device due to the turn-on of a real or parasitic thyristor by the passage of a single energetic particle through sensitive regions of the device structure, and resulting in the loss of device functionality.

NOTE 1 A high-current SEL event may result in catastrophic permanent damage or in latent damage to the device.

NOTE 2 A micro-SEL event (e.g., latch-up of memory cells within a common well) might result in an undetectable change in current compared to the quiescent current of the device. These events are typically non-destructive but can impact the device lifetime due to the localized current draw. Normal operation can be restored by power cycling of the device (off and back on).

3 Terms and definitions (cont'd)

single-event transient (SET): A momentary voltage excursion (voltage spike) at a node in an integrated circuit caused by the passage of a single energetic particle.

NOTE SETs can occur in digital logic (DSETs) where they can propagate to a bi-stable element and become an SEU, and in analog linear circuits (ASETs), where they can propagate to the output node.

single-event upset (SEU): The change of a bi-stable node state from one to zero, or vice versa, due to the passage of a single energetic particle.

NOTE 1 SEU, including SBU, MBU, and MCU, is typically "soft" because the affected nodes can be rewritten and behave normally thereafter.

NOTE 2 An SEU that results in a change in device functionality requiring intervention is defined instead as a SEFI.

stuck bit: A single-bit error that cannot be corrected by rewriting or power cycling.

threshold LET: The minimum linear energy threshold (LET) required to cause a single-event effect (SEE).

4 Beam dosimetry

4.1 Overview

When performing single-event effects testing, the user has the ultimate responsibility for assuring that the beam conditions are correct. The analysis of the beam should be divided into two main tasks. First, when using beam lines in development or that do not have known, consistent beam energy spread and purity, it is important to measure the energy and purity of the beam. The beam should be composed of one ion species with a tight energy distribution. The level of any contaminants must be assessed in terms of their impact on the DUT data. Second, it is important to measure the ion flux and the spatial uniformity of the beam regardless of beam-line maturity. The user shall establish with the test facility in advance of the test the level of dosimetry support that will be provided.

4.2 Beam energy and purity

4.2.1 General

The accelerator facility shall be capable of delivering heavy ions of suitable LET, energy, and species. A beam energy within 10% of the desired energy should be adequate. If degraders are used in the beam path, the full energy spectrum after the degrader shall be measured (see 4.2.3.1) or calculated. Any additional materials in the beam path up to the active layer of the device must be accounted for when identifying the test energy and LET, and to ensure adequate ion penetration range.

Beam impurity should be low enough not to impact the DUT data. Acceptable levels will depend on the Z of the contaminant. In general, a 1% impurity may prove acceptable.

4.2.2 Specification and calibration of the measurement system

The energy measurement system must have the capability to determine the beam energy and the proper elemental ion selection. A surface barrier detector is typically used to measure the beam energy spectrum and purity [4] and must have a depletion region larger than the range of the ion for the energy of interest so that the maximum ionizing energy will be collected.

The system must be calibrated to a known energy. Corrections must be made for the ion energy deposited in the layers of the detector with negligible charge collection efficiency, referred to as dead layers. In addition, the charge collection efficiency of a surface barrier detector will change due to the lattice damage that builds up over the lifetime of the detector; in order to account for changes in charge collection efficiency, the detector must be recalibrated before use. Calibration is achieved by exposing the detector to an alpha particle source such as americium-214 (Am), of a known energy. See IEEE STD 300 for measurement procedures. Detector system vendors may also provide calibration procedures. These alpha particles can also be used to determine the thickness/density of the foils used for the LET measurement in 4.2.3.2.

4.2.3 Measurement procedure

4.2.3.1 Energy and purity measurements

1. Reduce the beam flux until surface barrier detector current pulses do not overlap.

2. Record a sufficient number of pulses to identify whether the required beam energy and purity tolerances have been met.

3. Determine the beam energy spread by generating a histogram of the current pulse heights.

4. Determine the beam purity from the histogram of the current pulse heights.

Beam contamination will be indicated by the presence of more than one peak in the histogram, although nuclear interactions between the ion and the detector can result in secondary peaks as well [4]. The user must notify the beam operator of detectable contamination in the beam; the beam is purified by using focusing magnets which are controlled by the beam operator. In some cases there may be a very low contamination peak that the operator will find difficult to remove. As indicated previously, the user must then decide if this contamination level is acceptable.

4.2.3.2 LET measurements

5. Place a thin foil of known thickness and density over a portion of the surface barrier detector.

6. Reduce the beam flux until current pulses do not overlap.

7. Record a sufficient number of pulses to clearly identify two energy peaks.

8. Calculate the energy lost in the thin foil by determining the difference in energy between the two peaks, and, using the known foil properties, translate the energy into the LET for the beam.

4.3 Beam flux and fluence

4.3.1 General

The heavy-ion accelerator shall be capable of delivering appropriate flux for the test. Beam fluence shall be spatially uniform across the area of the device to within ± 10% of the mean fluence. The flux and fluence of the beam are determined by using scintillation detectors, and the dosimetry system should allow for continuous monitoring of the flux at the device location throughout the test with an accuracy of ± 10%. Some specialized low-flux and/or low-fluence tests will be inherently unable to meet these uniformity requirements and any impact on the data collected should be assessed.

4.3.2 Measurement

The user shall verify that the facility has a beam flux and fluence measurement system in place and that the requirements in 4.3.1 are met.

5 Test plan

5.1 General overview

A test plan shall be developed to support each test. The test plan will serve as a guide for the procedures and real time decisions to be made during the actual irradiation period. However, no test plan can be followed exclusively because accelerator variables and the results of the earlier runs may affect later decisions. Three useful documents to aid test planning include [5] for FPGA testing, [6] for scaled CMOS memories, [7] for linear device SET testing, and [8] for more general SEE test guidance. Also reference the test plan sections found in ESA/SCC 25100 and ASTM F1192 for additional guidance. See Annex B for a description of test elements.

5.2 Test plan contents

5.2.1 Purpose or objective of the test

5.2.2 Devices to be tested

5.2.2.1 Device information

The following device information shall be provided:

- Manufacturer and part number
- Generic part number (if applicable)
- Description
- Technology
- Packaging
- Provenance of the parts (e.g., lot date code, wafer and assembly lot number, etc.)
- Preparation needed (decapsulation/delidding, die thinning, etc.)
- Sample size and number of control devices
- Sample selection process

5.2.2.2 Sample size

The homogeneity of the device lot should be considered, and the largest sample size possible used. For example, in SEE qualification testing, MIL-PRF-38535 Group E Subgroup 5 (Single-event effects test) requires 4 samples to be tested with all 4 parts meeting the manufacturer's rated specifications. Non-qualification tests should comprise of a sample size practicable to establish statistical confidence in the data set, as defined, for example, in MIL-HDBK-814.

NOTE Statistical confidence in the data set is increased through capture of a large number of events and/or a large number of device samples, and thus depends on whether the SEE results in permanent damage, the extent of process variability that may impact the SEE response, the confidence in the test setup, and other variables.

5.2.3 Test facility information

5.2.4 Test Setup

5.2.4.1 General requirements

A description of the test setup, including test equipment, cabling, test board schematics, software, any thermal management of the DUTs, and the physical arrangement of the setup as it will be implemented at the test facility shall be included. No DUT pins should remain floating: if left unbiased, they should be shorted or grounded to avoid damage to the DUT from charge buildup. See Annex B for a discussion of the test equipment. Potential interferences (see Annex A) must be considered when designing the test setup.

5.2.4.2 Single-event latchup testing capability

Single-event latchup can result in the catastrophic failure of some device types; thus, power supply limiting or power line resistors may be required to prevent a device failure. If mitigation is used, the experimenter shall verify that the mitigation has not distorted the latchup detection. Test plans shall also include steps for verification that any current limits reached are due to SEL (see 5.2.7). The test system shall incorporate the capability to monitor the occurrence of latchup, as well as the ability to reset the DUT.

5.2.4.3 Single-event burnout testing capability

Single-event burnout can result in catastrophic failure of the DUT. In some devices, SEB characterization tests can be performed using an SEB circumvention and monitoring circuit such as that shown in Annex C. At the end of protective-mode SEB testing, the protection circuitry shall be removed and the threshold for SEB verified destructively. Verification testing (see 7.7.1.2) is typically performed without SEB circumvention.

5.2.4.4 Single-event transient testing capability

SET sensitivity and characteristics of linear devices are highly dependent on output load conditions. Attention must be given to the test setup, including cabling, test board design, and equipment, to minimize parasitic capacitance and resistance which will reduce the SET amplitude and increase the width, respectively. Parasitics can also introduce oscillations in the SET pulse. Where possible, an active oscilloscope probe having low capacitance should be used. The test setup must be capable of capturing and saving both positive and negative (and bipolar) transients. A minimum SET magnitude and duration of interest should be defined; the test setup should be sensitive enough to measure these minimum SET characteristics.

For digital parts, on-chip counting circuits are required, and the resulting SET test methodology is out of the scope of this document. See [12] and references therein for information on this topic.

5.2.5 Test conditions

5.2.5.1 General overview

A test matrix shall be established that encompasses the device, test program, and beam conditions. Tests shall be performed under application-specific conditions or worst-case conditions for the device type (see 5.2.5.3), unless otherwise agreed to by the parties involved in the test.

5.2.5.2 Test matrix

The test matrix must include at a minimum, as applicable:

Description of the device configuration including:

- operational mode
- input pattern or stimulus
- electrical bias
- case temperature
- current-limiting condition
- frequency or clock rate
- reset condition

Beam conditions:

- energy, ion species, range, and LET
- flux
- fluence
- angle(s) of beam incidence

5.2.5.3 Worst-case device operating conditions

As a general rule, the worst-case test conditions are as follows:

- SEU (SBU/MBU): minimum operating voltage, maximum clock frequency; if passive elements such as resistors are designed into the integrated circuit, case temperatures resulting in decreased resistance will increase SEU susceptibility (for example, IC devices incorporating lightly-doped polysilicon resistors increase SEU sensitivity with increasing case temperature [7]).
- SET: there is no broadly applicable worst-case operating condition. It must be experimentally determined for a given device.
- SEL: maximum operating voltage and maximum operating case temperature.
- SEB: maximum reverse-bias voltage and minimum operating case temperature.
- SEGR: maximum gate bias; if power MOSFET, maximum drain-source bias under maximum off-state gate bias. Temperature is not a primary factor.

Due to potentially competing mechanisms, however, actual worst-case conditions should be ascertained for each device type. Complex device susceptibility to SEE may depend on the particular state it is in when the ion strikes the sensitive node. This variable sensitivity can give rise to time/state dependent behavior. In this case, testing should be performed in a near-flight-like configuration or a bounding state of operation, if known, to ensure the device spends an adequate amount of time in the state of susceptibility. There may be different worst-case states for different error modes.

5.2.6 DUT failure criteria

If applicable, indicate the basis for designating DUT failure.

5.2.7 SEE detection methods

The expected error and/or failure modes shall be provided in the test plan along with the methods to be used for SEE detection. The basis for detecting SEE must be defined by a comparison of the test device response with some reference state(s), or post-irradiation bit patterns or current levels with the pre-irradiation pattern or current levels. Tests of SETs require special techniques whose extent depends on the definitions of the SET and the objectives and resources of the experimenter: for SETs on the output of linear devices, the oscilloscope trigger setting will be defined either by an application minimum SET pulse magnitude or duration of concern, or to the lowest level possible in order to capture all transients for characterization of amplitude and duration.

Test plans should include methods for differentiating failure modes such as, for example, MBU and SEFI, SEL and SEB or SEFI, and SEGR and SEB.

5.2.8 Beam characteristics

5.2.8.1 General overview

Included in the planned test matrix (section 5.2.5.2) are the species and characteristics of the heavy-ion source to be used, as well as angles of incidence on the DUT. These elements will depend on the test goals (for example, SEE cross section versus LET curve, or SEGR or SEB response curve). Real-time decisions of beam characteristics may be required based on initial test results.

When planning tests at angles other than normal incidence to the DUT, care must be taken to prevent the test setup and DUT packaging from shadowing the beam. Any obstruction in the ion beam path to the DUT will result in uncertainty in the beam fluence and can broaden the beam energy spectrum.

In-air testing requires determination of ion energy and range at the surface of the DUT to ensure sufficient penetration range through the charge-collection region of the device. When materials are placed in the beam path to vary the beam energy or LET, the test plan shall include determination of degrader thicknesses, air gap between the beam exit port and die surface, etc. required to achieve the target beam characteristics. The test plan shall include an analysis of the impact of these materials on the spectrum of energies/LETs at the die surface and/or active region of the device.

Test planning must account for the time required for facility personnel to bring the beam to specification from the off condition or from a different beam energy tune, and for switching ion species/energy. These times can vary substantially between facilities. Users should check with the facility to determine what time penalties will be incurred based upon the beam tuning that is anticipated, and work with the facility to optimize the ion selection flow.

5.2.8.2 SEE cross section versus LET curve

Ion species and energies shall be chosen to cover the energy or LET range necessary to determine the SEE threshold, saturated or maximum cross section, and for full device characterization, the shape of the curve between threshold and saturated or maximum value (see 7.6.2).

The test plan shall include evaluation of the ion penetration depth in relationship to the deepest sensitive junction, with the goal of maintaining constant LET through the sensitive volume for all angles of incidence to be tested. This evaluation will require awareness of the material and thickness uncertainties for a particular stack-up.

Changing the angle to change the effective LET can be useful for SEU and SEL, and in some lateral power or radio-frequency (RF) MOSFETs, for SEB. Effective LET should not be used in devices susceptible to MBUs or SEGR, and does not apply to SEEs in any device whose sensitive volume is deep compared with the extent of its lateral dimensions.

See Annex A.6 – A.9 for additional precautions.

5.2.8.3 SEGR and SEB response curves

For SEGR and SEB testing, the safe operation conditions are mapped for several ion species (see 7.7.2.2). SEGR susceptibility is a function of both the ion species and its energy (penetration range in the device) or LET; LET therefore cannot be used as a single metric for beam selection [8]. Effective LET should not be used in devices susceptible to SEGR, and does not apply to SEEs in any device whose sensitive volume is deep compared with the extent of its lateral dimensions. See A.6 for additional precautions regarding LET.

The selection of the test ion species for discrete vertical, planar-gate power MOSFETs is limited by ion penetration range, such that worst-case ion energy for the given species must be achievable at the test facility. Maximum SEGR and often, SEB sensitivity occurs with the beam at normal incidence to the die and when maximum energy for a given ion species is deposited in the sensitive volume (the epilayer(s)). The worst-case surface-incident ion beam energy can be approximated prior to testing the device through the use of energy (LET) vs. penetration depth curves for the given ion species if the sensitive volume depth is known. If the sensitive volume depth is unknown, characterization should be performed for several energies per species to demonstrate that the worst-case ion beam energy has been identified.

For other types of devices, if the device sensitive volume is shallow enough that the ions will have near-constant LET through the volume (typical of modern integrated circuits and lateral power MOSFETs), a worst-case test energy does not apply.

5.2.9 Dosimetry

The equipment and techniques needed to measure the ion beam flux, fluence, energy, and uniformity must be identified. The equipment and techniques may be provided by the accelerator facility.

5.2.10 Flux range

The range of heavy-ion fluxes (both average and instantaneous) must be established to provide the valid dosimetry and assure that all effects on device response are due to single ion strikes independent of previous ion strikes. For SEE testing a typical ion flux range is $1x10^3$ $cm^{-2}\cdot s^{-1}$ to $1x10^5$ $cm^{-2}\cdot s^{-1}$. However, higher fluxes may be acceptable if it can be established that these high-flux conditions do not invalidate the test results due to problems with dosimetry, tester limits, device heating, and/or charge pile-up effects (examples include effects due to accumulation of charge from more than one ion, false MBU counts when performing SRAM read-back during irradiation, etc.) in the device under test. It should be demonstrated that the device response as a function of flux remains linear at the desired test flux such that the event cross section is independent of flux.

NOTE In some devices, high-flux interferences may necessitate beam fluxes below $1x10^3$ $cm^{-2}\cdot s^{-1}$. In addition, lower flux may be necessary to prevent overlapping events such as SETs or to protect the part during SEL testing.

5.2.11 Particle fluence levels

The appropriate particle fluence level is a function of the test particle kinematics, the number and size of device sensitive nodes/transistors, the number of samples to be tested, and the dynamic operation of the device. The total number of particles must be sufficient to establish with a high statistical confidence that all sensitive volume(s) in the DUT have been irradiated or that for the given mission environment and number of devices to be flown, the likelihood of a rare event determined from

$$\sigma = \frac{3.7}{\text{fluence of no errors x } \cos(\theta)},$$

where σ is the event cross section and θ is the beam angle of incidence, is acceptably low for the mission risk tolerance. In the equation above, the use of 3.7 bounds the cross section at 95% confidence when no events are measured (see [3] and Annex A.10). Dynamic operation introduces to geometric-coverage considerations the need for statistically sufficient (for a given risk tolerance) state and temporal coverage. Sufficient geometric and temporal sampling is most critical when establishing the threshold LET where very few events occur.

Historically, as suggested in ASTM 1192, an ion fluence of $1x10^7$ cm^{-2} has proved adequate. For the region above the onset threshold, typically an ion fluence of $1x10^6$ or 100 observed errors may be sufficient. More advanced/complex technologies may require higher fluence due to lower event rates, and 100 non-destructive errors may not be realistic for these smaller cross-section events. For SEGR or SEB testing, a minimum ion fluence of $5x10^5$ cm^{-2} is used for large, discrete devices, though a higher fluence is warranted when device homogeneity is uncertain and/or when substantial part-to-part variability occurs at this minimum fluence. For small, integrated devices, $1x10^7$ cm^{-2} is recommended as a minimum for SEGR or SEB testing.

Higher fluence than the typical levels given above are required for certain structures. Deep sub-micron CMOS devices with high cell densities such as SDRAMs will require higher fluence and sampling of each cell/sensitive volume may not be practicable [6]. In this case, the per-bit upset cross section defined in clause 3 shall be scaled. Test structures will require higher fluence to reveal rare events.

When selecting a fluence level, dose effects must be considered for the time the DUT is under irradiation.

5.2.12 Accumulated ionizing dose

The total accumulated ionizing dose for the sum of all planned irradiations shall be recorded for each device (see Annex A.4). Estimates of the DUT tolerance to ionizing dose shall be provided.

6 Pretest procedures: Before arrival at the test facility

6.1 Test plan preparation

Prepare test plan per clause 5.

6.2 Device preparation

6.2.1 Decapsulation

Devices must be delidded/decapsulated to permit access of the heavy-ion beam to the chip face. Testing at a high-energy ion facility may obviate this requirement. If special barrier materials (for example, polyimide, silica gel, and the like) have been used to coat the chip for alpha particle protection, stress relief of bond wires, or electrical protection, they must either be removed or characterized for thickness and uniformity to verify that the ion energy loss to these coatings will not result in LET non-uniformity or inadequate penetration range in the SEE sensitive volume. If the coating will interfere, it must be removed using the manufacturer's recommended procedure, if known. Die passivation layer(s) should remain intact. See also Annex A.8.

Preparation procedure:

1. Verify the electrical performance of the DUT.
2. Delid or decapsulate the device, removing any die coatings if appropriate.
3. Re-verify the electrical performance to ensure no damage or changes in performance have occurred.

NOTE Some high-voltage devices can arc when die coatings are removed and rated biases are applied. This vulnerability can be enhanced when testing in vacuum. Arcing can be prevented through a well-controlled, uniform application of an insulating conformal coating (such as parylene) of known thickness. The coating will affect the ion beam energy, penetration range, and LET; this impact must be calculated to determine that appropriate ion penetration depth in the device will be achieved during irradiation (see 5.2.8.3).

6.2.2 Die thinning

Flip-chip packaging and die with extensive overlayer metallization can necessitate irradiation through the backside of the die. Die substrates must be carefully thinned if the ion penetration range is insufficient to provide a near-constant LET through the sensitive volume or if the ion energy spread due to passage of the beam through the substrate is too broad for data interpretation. The electrical configuration of the thinned part should be studied and characterized before attempting SEE testing: thinned parts often have greatly reduced power dissipation capabilities which can result in the inability to operate the part in its normal configuration and at its rated speed and supply voltage. In addition, the heavy-ion response of the thinned part can be altered if diffusion of charge from the substrate plays a role in the SEE mechanism and the substrate thinning impacts this charge collection volume. Finally, the part may become mechanically fragile and thus vulnerable to failure during shipping or handling.

6.3 Test setup check-out

Validate the entire test setup as a system before shipping to the heavy-ion accelerator facility. This pre-test validation shall include all software, hardware (DUTs, cables), fixtures and interfaces. Cable lengths equivalent to those at the test facility must be used to reduce the risk of unanticipated noise, power loss, RF, or other issues interfering with reliable data capture. Care should be taken to prevent mechanical stress on the cables. Each DUT should be functionally and parametrically verified prior to departure.

7 Testing procedures

7.1 General overview

Clause 7, subclauses 7.1 through 7.5 contain general test procedures for most heavy-ion testing. Different test goals (data sets) will require different additional operating procedures. The following procedures are covered in the subclauses indicated:

- SEE cross-section curve data collection – 7.6
- SEGR and/or SEB safe operation data collection – 7.7
- SET characterization of analog and digital circuits – 7.8

7.2 DUT handling

All parts must be handled with the precautions for parts susceptible to damage from electrostatic discharge. The use of ground planes and straps is highly recommended whenever possible. In addition, decapsulated/delidded parts must be protected from damage to bond wires and die surfaces, and die that have been thinned must be additionally protected, if susceptible, from mechanical stress and cracking.

7.3 Standard operating procedure

Before beginning irradiation, ensure that all personnel are properly trained on safety issues, hazard mitigation techniques, that the test equipment has been properly setup, and that the radiation source is operating as expected. Setup conditions vary with each facility.

7.4 Beam setup

Request the desired beam characteristics from the facility operators. At this point, facility personnel should begin tuning the accelerator for the required experimental conditions. Such tuning may include establishing the desired flux, ion species, purity, energy, and uniformity. The exact sequence will depend on the facility and beam requirements. See 5.2.8.1 regarding facility time necessary for this activity.

7.5 Setup procedure

7.5.1 Test equipment location

The test equipment should be set up as close to the DUT holder as possible (see 6.3). Ensure that the equipment does not interfere with the movement of the DUT x-y stage.

7.5.2 Test fixture mounting

Position the DUT test fixture on the stage mounting bracket. Ensure that cables to the test fixture do not limit the free movement of the x-y stage (and rotation, if used), and that the cables will not shadow the DUT from the beam. Verify that the DUT will be in the beam path; some facilities are equipped with a built-in He-Ne laser which can be used for this verification.

7.5.3 Setup check

Check for correct setup of the equipment by testing each pin of the DUT socket, where applicable.

7.5.4 Control part/test board check

A control part should be inserted in the DUT socket (or a control test board used) and checked for correct performance. If part/test board performance differs significantly from earlier measurements on this part/test board, debug and correct the system, repeating procedures as outlined in 7.5.1, 7.5.2, and 7.5.3 as appropriate.

7.5.5 Photograph Record

The test setup including fixtures and equipment and their placement relative to the beam port should be photographed for test method documentation.

7.5.6 Load DUT and prepare vacuum chamber (if used)

7.5.6.1 In-air testing

Position the devices to be tested in the DUT fixture. Check alignment and position of each loaded socket on the DUT fixture; if applicable, use the built-in He-Ne laser for greater accuracy. Record position.

7.5.6.2 Vacuum-chamber testing

If testing in vacuum, depending upon the facility system, alignment per 7.5.6.1 can be performed with the system vented or with the system under vacuum.

Close vacuum chamber and initiate pump-down sequence.

7.5.7 Measure and record the ambient temperature in the vicinity of the DUT, and/or the DUT temperature

For experimental measurement repeatability/reproducibility, test temperature conditions should be documented. These may include the ambient environment temperature and/or the temperature of the DUT itself when practicable.

7.5.8 Measure beam energy (if applicable)

Measure the beam energy using the surface barrier detector(s) in the beam diagnostic chamber (see 4.2.3). Refer to the SEE test facility operation manual for the specific detector to use with specific ions. If the ion energy varies significantly from the requested value, or if more than one peak is observed in the energy spectrum, notify the operator to retune the accelerator.

NOTE The surface barrier detector(s) should be checked for calibration at least once during the SEE test campaign.

7.5.9 Measure LET (if applicable)

Measure the beam LET using the specific detector for the ion species in use (see 4.2.3). Refer to the SEE test facility operation manual. If the LET varies significantly from the expected value (+/- 10%), notify the operator to retune the beam if necessary.

NOTE 1 Many facilities determine LET from the beam energy and ion species using software to calculate the stopping power, as opposed to making detector measurements. If the facility does not provide LET information, the user must perform the calculation using standard software for this purpose.

NOTE 2 Care must be taken to understand LET at the surface of the sensitive volume considering device overlayers, any airgap between the beam exit port and the DUT, the window of the beam exit port, and any other attenuating materials. See also Annex A.6.4.

7.5.10 Measure beam uniformity

After the proper ion species and energy have been obtained, measure, and if necessary, adjust the beam uniformity. Adjustments using beam defocusing techniques, thin scattering foils, or both, should be performed by facility personnel to obtain the desired beam uniformity. Uniformity measurement of fluxes taken with detectors should be accurate enough to ensure that the fluence (cm^{-2}) counted by the measurement system scintillator is within 10% of the fluence impinging on the DUT.

7.5.11 Select the ion flux for SEE testing

Request that the operator provide the desired flux, or if user-accessible, remove appropriate beam attenuators to achieve the desired flux.

7.5.12 Perform noise baseline test

Record the position of the DUT then move the stage so that the beam will strike a blank region on the test board or an empty socket. Open the beam shutter and record data from the DUT to establish a system noise baseline. Close the beam shutter and restore the DUT to its position in the beam line.

7.6 Operating procedure – SEE cross-section curve data collection

7.6.1 General procedure

In this procedure, the DUT operating conditions are fixed and the beam conditions are varied. The information obtained from the tests shall result in an SEE cross section versus LET plot or table that can be used to calculate the on-orbit SEE rate. This procedure can be repeated to assess different DUT operating conditions or modes.

7.6.2 How much cross-section data should be taken

Cross section versus LET data are used to calculate on-orbit SEE rates and are typically fit to a 4-parameter Weibull distribution; a minimum of 6 well-defined data points are recommended to give the fit predictive power [10]. Historically, data are taken up to 2X the LET required for the cross section to saturate. The saturation condition should be determined from a linear plot of the cross section. The purpose for the 2X margin is to ensure that the cross section is truly saturated; if the 2X level is not possible, data should be taken up to an LET(Si) of 80 MeV·cm^2/mg as deposited in the sensitive volume of the device or as dictated by the application.

7.6.2 How much cross-section data should be taken (cont'd)

In addition, a determination is made of the threshold LET below which no SEEs occur for the specified fluence. From this threshold LET and the saturated cross section, a rudimentary failure rate estimate can be made by assuming the cross section versus LET curve is a step function. Additional data should be taken at the following fractions of the maximum cross section:

- 75% to 80%, for information about the Weibull shape parameter.
- 50%, to characterize the median critical charge of the elements in the array.
- 25%, useful for a quick figure-of-merit type estimate of the upset rate [11].
- 10%, useful to compare with previous published data and for making estimates of the proton sensitivity through its relationship with the Bendel A parameter [11].

Most highly-scaled CMOS or advanced-technology device cross sections will not saturate. In these cases, data should be taken up to an LET(Si) of 80 MeV·cm^2/mg as deposited in the sensitive volume of the device, or per the survivability of the DUT or as agreed to by parties of the test. The threshold LET for these devices can be very low (< 1 MeV·cm^2/mg in silicon, for example). It is therefore important to obtain more extensive low-LET data due to the larger impact the shape of the curve in this region will have on the overall calculated SEE rate. See [13] for additional information on the influence of the cross-section curve on calculated SEE rates.

If the cross section approaches or exceeds the die size, it is often an indication of multiple upsets; in this case, all data should be examined and corrected for this effect. In all cases, the LET at the sensitive volume should be calculated carefully, accounting for the energy absorbing layers above the sensitive volume. See Annex A.6.1 – A.6.2 for additional considerations.

7.6.3 Setup

Set the device operating conditions per the experimental test plan.

7.6.4 DUT electrical check

Begin electrical test sequence on the DUT; check for correct operation.

7.6.5 Initiate testing

Open beam shutter and begin heavy-ion exposure of the DUT and record time.

7.6.6 Run conditions check

Monitor the error rate to ensure that errors are not being generated too rapidly or too slowly as discussed in 5.2.10.

NOTE There may be more than one error type. See Annex A.11.

7.6.7 Test performance

Expose DUT until the desired number of errors has been measured or the desired maximum fluence has been reached. Close shutter and record time and fluence.

7.6.8 Additional testing: If SEEs occur

If the device proves susceptible to SEEs, there are several options available for follow-on tests to complete the planned test program. Note the order of the following options will depend upon the capabilities of the test facility.

1) Change flux/fluence to get a statistically meaningful number of events without overloading the device tester or dosimetry. See 5.2.10 and 5.2.11.
2) Repeat runs two or three times as required to establish test repeatability or to verify beam stability.
3) Change beam tilt and/or roll angle to a) fill in a point on the cross section versus LET plot or confirm another measurement made with the same effective LET but with a different ion, energy, and angle combination; and/or b) identify angle dependencies of events as a function of both tilt angle and roll angle. When increasing the angle of incidence, ensure that the ion beam is not shadowed by the DUT package or other portions of the test setup.

   NOTE 1 Tilt describes the DUT angle with respect to the ion beam. Tilt varies from 0 to 90 degrees with reference to the ion beam axis. Tilt is often referred to as the angle of ion exposure and is utilized in the $1/\cos(\theta)$ relationship. Roll is the DUT facial orientation with reference to the normal of the ion beam. Roll can vary from 0 to 360 degrees. Roll is often referred to as rotation.

   NOTE 2 The cosine dependence for determining effective LET may not apply; see Annex A.

4) Change operating parameters including initial load configuration, clocking, operating mode, and for memories or shift registers, input data patterns.
5) Change to another temperature (if applicable).
6) Select another device of the same device type to measure part-to-part variability.
7) Select another ion species to introduce a new range of LET values.

7.6.9 Additional testing: If SEEs do not occur

If the device does not experience any SEEs in the initial run, the following test parameters can be varied as an attempt to obtain single events:

1) Verify test setup.
2) Verify adequacy of ion penetration range.
3) Increase fluence.
4) Increase beam tilt angle and/or change roll angle.
5) Change operating parameters, including initial loaded pattern when testing for SEUs or SEFIs. Some devices will only be susceptible to a given SEE when in a specific operating mode/state.
6) Vary voltage supply biases. A lower bias voltage (minimum of the specified operating range) promotes bit-flips and high bias (maximum specification) promotes latchup (this may not be true for SOI MOS devices). If the onset of SEE occurs with a small bias change, then this fact indicates that the original conditions are close to the threshold LET.
7) Select another device of the same type.
8) Select a higher-LET ion species.

7.7 Operating procedure – SEGR and/or SEB safe operation data collection

7.7.1 General procedure

7.7.1.1 Characterization

In this procedure, for a given beam condition, the DUT operating conditions are varied. The SEGR and/or SEB susceptibility of the particular semiconductor device is characterized as a function of bias voltage and beam conditions to define worst-case operating conditions and failure threshold curves. The bias voltage and currents of discrete devices can usually be sourced or measured directly. For these devices, characterization is performed as a function of V_{GS} (gate-source voltage) and/or V_{DS} (drain-source voltage), or as a function of V_R, as applicable, as well as ion species and energy. For integrated or hybrid devices, V_{GS}, V_{DS}, and/or V_R may not be directly accessible; instead, the input and output voltage, the output load, and/or the switching speed of the device are characterized as appropriate to indirectly vary the stress on the susceptible component, along with varying the species and energy of the ion beam.

Tests are conducted with the voltages or other stress conditions applied during the ion strike; for discrete power devices, tests are typically conducted with the device in an off-state bias condition. Additional post-irradiation electrical measurements are performed to verify device integrity. The device currents are then measured at the next bias increment prior to the next ion exposure. A typical characterization test flow is given in Annex C.

NOTE The sensitive charge collection volume of power devices is the epitaxial layer(s) and can extend to depths of 10s of micrometers in some vertical technologies. For this reason, in these thick-epilayer devices LET by itself is not an appropriate metric for device characterization. Instead, the ion range (energy) must be considered as well as the atomic number of the ion. For discrete planar-gate, vertical power MOSFETs, maximum sensitivity occurs with the beam at normal incidence to the die (i.e., parallel to the internal drift field) and for SEGR, when maximum energy for a given ion species is deposited in the sensitive volume (the epilayer(s)). Worst-case angle of incidence may differ for other device topologies.

7.7.1.2 Verification

Verification tests are performed under a specific set of device operating conditions and beam conditions. These tests yield a “pass/no pass” outcome useful for hardness assurance and qualification testing.

7.7.2 How much characterization test data should be taken

7.7.2.1 Device operating conditions

For discrete power MOSFETs, the off-state safe operating range should be mapped for various ion beam conditions. V_{DS} should be incremented by no more than 10% of the rated drain voltage (BV_{DSS}), and V_{GS} incremented by no more than 25% of the rated gate voltage. Similarly, for integrated or hybrid devices, the bias, load, frequency, or other stress conditions should be incremented in steps small enough to define the safe operating conditions for the given beam condition.

7.7.2.2 Beam conditions

SEGR susceptibility is a function of both the ion species and its energy (penetration range in the device); linear energy transfer (LET) therefore cannot be used as a single metric for beam selection. Tests are conducted under worst-case beam energy for a given ion species. The species to be used are determined by the device hardness to SEGR. Species are chosen to delineate the safe operating areas within which SEGR will not occur upon strikes by ions as heavy as or heavier than the test species. It is recommended that at least one ion species from each of the following groups (“bins”) be selected for device characterization: 1) Z = 29 (Cu) to Z = 36 (Kr); 2) Z = 39 (Y) to Z = 59 (Pr); and 3) $Z \geq 67$ (Ho). For devices experiencing no SEGR under maximum stress conditions when irradiated with species from bins 2 or 3, no tests with species from bin 1 are necessary. Conversely, if the device is highly susceptible to SEGR upon irradiation with a species from bin 1, it is generally not useful to pursue tests with ions from bin 3. Other considerations in ion selection include the risk aversion of the mission.

7.7.2.3 SEB cross-section data

Under protective mode testing (see Annex C for an example test circuit), SEB cross section versus LET or ion species can be obtained as per 7.6.

7.7.3 DUT electrical check

Tests should electrically stress the device at its maximum rated electrical conditions (or other conditions agreed upon by parties to the test). For discrete power MOSFETs, these tests include a gate stress test in which at 0 V_{DS}, the maximum rated gate bias is applied for 1 second and gate current measured (i.e., 1-second sustained I_{GSS} measurement), and a zero gate voltage drain leakage current (I_{DSS}) measurement or drain-source breakdown voltage (BV_{DSS}) measurement.

7.7.4 Apply bias to the DUT

Bias the DUT as defined in the test plan and record pre-irradiation currents and/or voltages.

7.7.5 Initiate testing

Open beam shutter and begin heavy-ion exposure of the DUT and record time.

7.7.6 Verify DUT operation

Observe the oscilloscope or equivalent output measurements to verify the DUT’s operation.

7.7.7 Terminate the beam run

Shutter the beam upon either reaching the fluence defined in the test plan or upon DUT degradation or failure prior to this total fluence being reached, and continue recording output measurements for several seconds before removing the test stress (bias) conditions.

7.7.8 Assess DUT for latent damage

For discrete power MOSFETs and integrated MOSFETs with accessible gate and drain nodes, perform a post-irradiation gate stress (PIGS) test by applying the maximum specified gate-source voltage to the gate terminal for 1 second and ensuring that the gate leakage current remains within its rated specification (this test may use either the specified positive or negative rated gate voltage or both conditions), and perform a zero gate voltage drain leakage current (I_{DSS}) measurement or drain-source breakdown voltage (BV_{DSS}) measurement.

For integrated devices without access to gate and drain nodes, apply maximum rated supply bias voltage conditions to verify device integrity.

7.7.9 Characterization testing

1. Repeat procedures as outlined in 7.7.4 through 7.7.8 at the next bias or load increment as indicated by the test plan.
2. Repeat procedures as outlined in 7.7.4 through 7.7.9 step 1 for as many samples as specified by the test plan.

7.7.10 Verification testing

Repeat procedures as outlined in 7.7.3 through 7.7.8 for as many samples as specified by the test plan.

7.8 Operating procedure – SET characterization of analog circuits

7.8.1 General procedure

In this procedure as applied to analog parts the DUT operating conditions are fixed and the ion beam conditions are varied, or the DUT operating conditions are varied for a given ion beam condition. The SET signatures are categorized and plotted by magnitude and duration. For SETs exceeding a given minimum magnitude and duration, a cross section versus LET curve can be obtained for rate determination, although currently, there is no agreed upon method for SET rate calculation. See Annex A.3 regarding the active fluence that must be used when determining the cross section.

7.8.2 How much SET data should be taken

7.8.2.1 SET pulse width and pulse magnitude characterization

7.8.2.1.1 General SET characterization

Data shall be taken on analog SET pulse width and pulse magnitude for pulses exceeding a defined minimum magnitude and/or duration, at DUT operating conditions and/or loads of interest. Characterization may be performed at multiple LETs per the test plan.

Approximately 100 pulses or more should be captured to create an envelope of the SET response for each DUT or beam condition. The pulses can then be plotted or histogrammed (see Annex C for a sample plot of pulse magnitude vs. width characterization). This characterization may be combined with the measurement of a cross section versus LET curve (see 7.8.2.2).

7.8.2.1.2 Worst-case SET characterization

To identify the worst-case SET, the maximum practicable LET shall be used. Data shall be taken on analog SET pulse width and pulse magnitude at worst-case DUT operating conditions and/or load conditions or at conditions as agreed to by parties of the test.

7.8.2.2 SET cross section versus LET curve

For pulses exceeding a defined minimum magnitude and/or duration, cross section versus LET data are used to calculate on-orbit SET rates and are typically fit to a 4-parameter Weibull distribution; a minimum of 6 well-defined data points are recommended to give the fit predictive power [10]. Historically, data are taken up to 2X the LET required for the cross section to saturate. The saturation condition should be determined from a linear plot of the cross section. The purpose for the 2X margin is to ensure that the cross section is truly saturated; if the 2X level is not possible, data should be taken up to an LET(Si) of 80 MeV·cm^2/mg as deposited in the sensitive volume of the device, or as dictated by the application or as agreed upon by parties to the test.

In addition, a determination is made of the threshold LET below which no SETs exceeding the defined minimum pulse occur for the specified fluence. Additional data should be taken at the following fractions of the maximum cross section:

- 75% to 80%, for information about the Weibull shape parameter.
- 50%, to characterize the median critical charge of the elements.
- 25%, useful for a quick figure-of-merit type estimate of the SET rate [11].
- 10%, useful for making estimates of the proton sensitivity through its relationship with the Bendel A parameter [11].

In addition to a cross section vs. LET curve for SETs exceeding a defined minimum SET, curves may be found for other SET thresholds or for ranges of SET magnitudes and/or durations.

7.8.3 Setup

Set the device operating conditions as specified in the experimental test plan. Set the beam energy and flux at the desired levels.

7.8.4 DUT electrical check

Run an electrical test sequence on the DUT to verify correct operation of the test fixturing and measurement equipment.

7.8.5 Initiate testing

Open the beam shutter, record time and begin heavy-ion exposure.

7.8.6 Run conditions check

Monitor the SET rate to ensure that errors are not being generated through high flux effects, that SET pulses are non-overlapping, and, for pulse characterization tests, that the SET frequency does not greatly exceed the download rate of the equipment used to capture the SET. See also Annex A.2.

7.8.7 Test performance

Expose the DUT until the desired number of SET events or the maximum fluence specified in the experimental test plan has been reached. A suitable fluence will range from 5 x 10^6 cm^{-2} to 1 x 10^7 cm^{-2}. Close the shutter and record the time and fluence. The sequence set forth in 7.8.3 through 7.8.7 shall be repeated for all samples, LET values, and SET definitions per the experimental test plan. The same definition of SET shall be used for a given set of LET values.

7.8.8 If SETs occur

Normally SET will be observed at all but the lowest LET values, and the test sequence can be completed as outlined in the experimental test plan.

7.8.9 If SETs do not occur

Nearly all parts will show an SET response, and the formal presence or absence of an SET depends on how the SET is defined. If a part does not show any SET, the amplitude or pulse width trigger or both are likely set too high for the LET being used. In this case, if appropriate, the definition of an SET must be changed until a statistically significant number of events is recorded, which typically (but not always) is 100 events. Such a change in the definition of SET will require retesting at the other LET values of interest; see 7.8.7.

8 Final report

8.1 Test data sheet

The test data sheet shall contain the following information:

1) Dates, times, names of test personnel.
2) Type of accelerator, name and location; ion species and energy tune.
3) DUT types, part number, serial numbers, functional description, technology, manufacturer, date code and mask number if known.
4) Device duty factor and fractional portion of the chip tested, if applicable.
5) Purpose for each test run and any changes from previous test run.
6) DUT operating parameters (bias, clock frequency, temperature, load, etc.)
7) DUT test patterns or operational modes, including duty factor.
8) Beam conditions including ion species, energy, and LET at the surface of the DUT or other appropriate reference location, air gap (if applicable), and angle of incidence.
9) Fluence, average flux, run time.
10) Number of errors, locations, and special comments (anomalous incidents).
11) Transient events and recovery time when instrumental.
12) Special test results, e.g., SEL, SEB, SEGR, SEFI, etc.

8.2 Test report

The test report shall contain the following information:

1) Test objective.
2) Complete description of the product(s) tested.
3) Description of test setup, test circuit diagram, and methods including device characterization and aliveness tests performed.
4) Complete description of beam conditions including methods used to determine the LET at the given reference location(s), DUT operating conditions during irradiation, and ambient conditions.
5) Summary of results including failure criteria as applicable.
6) Conclusions.

9 References

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Annex A (normative) – Interferences

A.1 Introduction

The major factors that can potentially interfere with the measurement and collection of heavy-ion test data useful for the prediction of application performance are herein described.

A.2 Ion beam flux

A.2.1 Beam calibration

To perform calibration of the ion beam, the flux must be reduced to assure that the rate of ion arrival does not impact the measurement.

A.2.2 Number of errors per unit time

To perform an SEE test, the DUT tester duty cycle must be adequate to handle the flux arriving at the DUT, or the flux must be reduced accordingly.

A.2.3 Charge pile-up

Excessive flux can result in charge pile-up, whereby measured effects are due to charge ionization from multiple ions. Care should be taken to determine that events are truly single-ion events.

A.3 Ion beam fluence

A.3.1 No event detected

In the case where no event is detected for a given fluence at a given LET, consideration should be given to the sensitive volume of the DUT with respect to the fluence required for one ion to strike the DUT at the location of the defined sensitive volume. For reasonable statistics, the fluence many need to be increased. The beam uniformity and DUT positioning should also be verified.

A.3.2 Determination of cross sections

The fluence used to determine an SEE cross section must only include “active” fluence time during which the test equipment and/or the device under test is available to count/measure/read the SEE. For example, during SET testing, the fluence that occurs during event storage time when no new events can be counted or recorded must not be included in the total fluence used to determine the SET cross section. Another example is when an SEU results in logical masking of errors: the fluence during the period of masking must not be included. A method for evaluating the amount of “inactive” time during the beam run is to vary the flux: if the cross section changes, then the amount of “inactive” time is too high.

Often, the cross section for the highest LET at which no event occurred (see A.3.1) assumes that the next ion after the beam was shuttered would have triggered an event. The cross section is therefore one event divided by the fluence.

NOTE When plotting a no event data point, it should be given a unique symbol to separate it from the true event detection data points. No event data can be plotted with error bars: the lower error bar will zero and the upper error bar for a 95% confidence level is 3.7 times the cross section (when calculated assuming one event) (see A.10 and [3]).

A.4 Ionizing dose damage

A.4.1 Ionizing dose history

A history of previous ionizing dose irradiation (both cobalt-60 or previous ion beam accumulation) for the DUT must be known to assist in the determination of whether prior ionizing dose has affected the SEE response.

A.4.2 Worst case ionizing dose

An estimate of the worst-case bound of ionizing dose, in units of rad(Si), can be made from the formula:

$$ID = 1.6x10^{-5}\ x\ LET\ x\ \varphi$$

where φ is the accumulated fluence in units of cm^{-2} and LET is in units of $MeV{\cdot}cm^2/mg$. The total ionizing dose for the different species is summed. The best current practice is to record the total fluence (cm^{-2}) each DUT receives for future analysis. It should be noted that the radiation damage from cobalt-60 and heavy ions may not be the same for equal dose in rad(Si).

A.5 Generalized noise

Grounding and shielding techniques must be optimized to reduce the possible effects of an electrically noisy environment.

A.6 LET

A.6.1 LET uncertainty

The energy loss of ions when passing through material is a stochastic process. For a given distance of travel through the material, a distribution of particle energies results. Energy straggle will be more pronounced when beam degraders are placed in the path of the beam and/or when performing back-side irradiations where the ions must travel through a substantial thickness of the die before reaching the charge collection volume. LET uncertainty increases near the Bragg peak due to the rapid change in energy loss with penetration range. In general, ion energies that result in the Bragg peak occurring before or in the sensitive volume should be avoided. Uncertainty in the materials and/or thicknesses of the die stack will limit the ability to determine the particle energy straggle and penetration range, and thus add to the uncertainty in particle LET.

The uncertainty in particle LET can be estimated using particle transport codes to determine the distribution for a given stack of materials. When possible, use the most recent release of the given particle transport code in order to obtain the most accurate LET values. X-error bars representing 1 or 2 standard deviations from the mean LET should be included in the resulting cross section vs. LET curve. In addition to LET uncertainty resulting from energy straggle or die stack unknowns, the methods for determining LET are inexact. It is therefore important to understand the method used by a given facility to calculate or measure the ion LET and the accuracy and/or precision of the method.

A.6.2 LET as a function of material

As indicated in clause 2, LET is strictly defined in terms of energy divided by distance but due to energy loss being directly proportional to the density of the material traversed, LET is typically divided by the density of that material, yielding units of $MeV \cdot cm^2/mg$, for example. Care should thus be taken when working with LET values. For example, when determining ion penetration range in a given material or calculating the average energy of an emerging ion, the LET for that given material must be used. Although the majority of semiconductor devices are fabricated in silicon, other materials such as silicon carbide and gallium nitride are becoming more common. Many cosmic-ray space environment models provide ion flux/fluence versus LET curves where LET has been normalized to the density of silicon. Similarly, most LET-based radiation performance or qualification requirements were derived from these curves and thus refer to LET in silicon (LET(Si)). When using heavy-ion test results to predict on-orbit performance, it is therefore important to define cross section data as a function of LET(Si) (regardless of actual device sensitive volume material) when working with environment spectra given as a function of LET(Si). Additionally, ion species and energy used for heavy-ion testing to meet LET requirements must yield the LET value for the material assumed by the requirement (typically silicon).

A.6.3 Highest LET at which no event occurs

The LET at which no event was detected prior to the next higher LET where events were detected is a function of the LET resolution of the facility. When plotting data points on a cross section versus LET curve, interpolation of LET between two LET data acquisition points is not done.

A.6.4 Effective LET

Different ions that have the same effective LET and different angular paths do not always produce the same device response. It is highly desirable to have overlapping data (several species and angles with the same effective LET) so that a comparison can be made. This is especially important if the $\cos(\theta)$ dependence seems to be violated. As an example, the sensitivity of vertical power MOSFET SEGR failures often *decreases* with increasing off-normal angle of incidence; effective LET is therefore not valid for these devices.

A.7 Overlayers

The overlayers (heavily doped drain, glass passivation, metal interconnects, etc.) above the sensitive volume reduce the energy of the ion before it enters the sensitive volume. Because the amount of charge deposited in the sensitive volume is a function of the ion energy, the assumed deposited charge may be in error. This energy loss may be calculated using the appropriate computer codes or published tables. This effect must not be ignored.

A.8 Die encapsulants/packaging

Delidded/decapsulation may result in loss of part functionality; it may be necessary to start with a larger population of parts to achieve the desired yield. If DUTs have a polyimide or other coating, it must be removed before SEE testing unless analysis determines that it will not interfere with ion penetration range or near-constant LET requirements, and is of sufficient uniform thickness that it does not introduce significant variability in ion energy as a function of die surface location.

A.9 Package shadowing

At large angles, the cavity of the device package may shadow a portion of the active surface area from the beam. This shadowing creates misleading data and must be avoided. A positive identification of clear beam path at a given angle is required as part of the test system setup.

A.10 Cross-section error

SEE data are inherently statistical, and in general SEE data are described by Poisson statistics. Where applicable, it is suggested to plot data with "two sigma" error bars that represent a confidence level of approximately 95%. For N number of events where N exceeds 50, the error bars will be +/- $2/\sqrt{N}$. For fewer numbers of events, a more rigorous approach must be taken. A useful guide to implementation of SEE error-bars is given in [3]. This method uses the inverse-chi-squared function which can be found in Microsoft Excel. In Excel, for the lower error bar use "=IF(N>0,0.5*CHISQ.INV((1-CL)/2,2*N),0)", where CL is the confidence level and the if/then notation handles the N=0 case, upon which the output is forced to 0. For the upper error bar, use "=0.5*CHISQ.INV(0.5+CL/2,2*N+2)". For an example SEU plot with error-bars, see Figure C.6.

A.11 Multiple error modes

When testing devices that are susceptible to more than one SEE mode, a given mode can interfere by masking the observation of the other error mode(s) and thus the true cross section versus LET curve for the mode(s). For example, if an SDRAM SEFI cross section is greater than that for SEUs, the SEFIs can limit the ability to obtain SEU data. Similarly, if an SEE mode (such as non-destructive SEL) has a much greater cross section than that of the mode of most concern (destructive SEL, for example), the mode of lesser concern may preclude the ability to detect the mode of greatest concern.

A.12 Latchup

Latchup testing must be performed at the maximum rated operating voltage and temperature. This is the worst-case condition for latchup. It is also important that the power supply be capable of constantly delivering enough current to the DUT so that a latchup condition can be initiated and maintained until it can be observed. Current limiting is normally employed to reduce burnout during latchup while allowing initiation of latchup. An automated system that can sense a latchup event and remove power from the DUT as soon as practical should be implemented to minimize damage. Latchup can cause DUT heating or damage that may impact subsequent SEL test data. In some cases, the latchup condition may be limited to just a small section of the DUT. Under this condition, it may be very hard to tell if a latchup condition occurred by monitoring supply current. Because of this uncertainty it is important to check the functionality of the DUT during latchup testing; determination that latchup has occurred should be made on a case-to-case basis.

A.13 Current sourcing and parasitic impedance

Destructive testing can place a sudden, transient high power demand on power supplies that can result in temporary sagging of bias voltage at the DUT. This drop in applied bias can result in device recovery such that the latchup or burnout condition is not fully initiated. Similarly, parasitic impedances can quench catastrophic SEE. Power supply limitations and parasitic impedances can thus interfere with the determination of device susceptibility to these catastrophic failure modes and must be considered. Stiffening capacitors located as close to the DUT as possible are used to source the transient current demand, preventing voltage sagging that would not occur in the device application circuitry.

Annex B (normative) - Equipment

B.1 Radiation sources and test apparatus

B.1.1 System characteristics

This test method is limited to use with either Cyclotron or Van de Graaff accelerators. In addition to supplying a beam, the test facility and/or user must also provide a vacuum chamber if needed, beam diagnostics, and a DUT stage.

B.1.2 Available ions/energies

The design of the ion source and the requirements for the method of acceleration will determine which ions are available. The accelerator design will determine the maximum energy that can be obtained.

B.1.3 Ion source

The ion source provides ions for acceleration. An ion source ionizes atoms containing the nuclear species by various methods: arc, radio frequency (rf), plasma, hot filament, electron bombardment, etc. The ions then go through a pre-acceleration and are put through an analyzer magnet to select a nuclear species and charge state. The ions are then injected into the main accelerator.

B.1.4 Cyclotron accelerator

A Cyclotron accelerates the ions provided by the ion source. A very large magnet produces a carefully shaped magnetic field that causes the ions to orbit around the centerline. This orbit is enclosed with a cylindrical metal pill box which has been cut in two along a diameter and are called the "Ds". The Ds have an rf potential imposed in the gap between them. Ions crossing this gap at the right time are accelerated. Ions out of phase with the rf potential are lost. As the in-phase ions are accelerated they spiral outward. When the orbit reaches the largest orbit sustainable by the magnet an extractor directs each clump of ions into a beam port where they enter the experimental area.

B.1.5 Tandem Van de Graaff accelerator

A tandem Van de Graaff accelerates ions using a dc electrostatic potential between a terminal and the outside at ground potential. Van de Graaff accelerators use a particular method (a belt) to charge the terminals. A Tandem Van de Graaff uses two terminals, accelerating negative ions from a negative terminal or a terminal at ground potential to a positive terminal where the electrons are stripped making positive ions. The positive ions are then accelerated between the positive terminal and ground.

B.2 Test instrumentation

The test instrumentation can be divided into two categories:

1) Beam diagnostics. This includes beam delivery, characterization, and dosimetry.
2) DUT test system. This system consists of the input stimulus generator and response recorder, which would be designed to accommodate the specified device.

Only the DUT test system is presented in this annex.

B.3 DUT test system

B.3.1 Physical setup considerations

The test board serves two purposes: first, it provides a stable mechanical interface to the test stage and second, it provides electrical interconnection between the DUT and the external support equipment. The test board is mounted to a stage inside the vacuum system or in air. The test board and stage must be capable of positioning each DUT on the test board accurately in the path of the beam. The stage must also be able to rotate the DUT accurately in order to modify the effective LET or characterize the device as a function of angle of beam incidence. Before designing the test board, it is critical that a template for the stage mounting be obtained, as well as information on the available vacuum chamber electrical feed-throughs when testing will be performed in vacuum.

Two distinct designs for the test setup are available for testing in vacuum: a self-contained unit which can be mounted within the vacuum chamber or a stimulator that resides outside of the chamber. The major advantages for the self-contained unit are the interface speed and simplicity whereas the major advantage for an external stimulator is the ability to modify the test setup without opening the vacuum chamber.

Similarly, when testing in air, a self-contained system residing fully in the ion beam cave can be used or a portion of the test equipment can reside in the user control room with cables running to the test board in the cave. The self-contained unit increases interface speed and simplicity and reduces parasitic capacitances and resistances from long cabling; alternatively, test setups within the control room can be modified without need for time-consuming entries to the beam cave.

B.3.2 Test modes

Both ac (dynamic) and dc (static) test modes are desired. Dynamic testing assures that input stimuli and circuit changes are coincident demonstrating failure modes that would only be apparent under these conditions (i.e., write failures in SRAMs). Static mode testing is desirable because some circuits are more sensitive after circuit relaxation has occurred (i.e., DRAM discharges during static conditions). It is also often easier to ascertain transients during a static test since the output state can be monitored continuously.

All DUT pins should either be biased, grounded, or shorted; pins that are left floating can buildup charge that upon uncontrolled discharge can damage the DUT.

B.3.3 Basic requirements

The basic requirements for the DUT test system are as follows:

1) Create test conditions for input into the DUT.
2) Identify, record, and correct any errors based on the selected test conditions.
3) Enable fault coverage evaluation. When designing the test system, the experimenter must understand the portion of the die, path, and latch of the device being tested in order to arrive at a quantitative result. The fraction of the time the device is in an SEE-susceptible mode and what fraction of the chip's susceptible elements is not tested should be known. Complex devices do not always permit easy testing access.

B.3.4 Basic capabilities

The DUT test system should be capable of:

1) Control of device initialization and rudimentary functional checks.
2) Device operation (dynamic or static operation while under irradiation and device resetting capability).
3) Error detection and logging.
4) Operation at, or near, the rated or application clock cycle for the DUT (when test is being performed in the dynamic mode).
5) Generation of a known duty factor (ratio of device "sensitive" time to total elapsed time). Knowledge of the duty factor is required to quantify device vulnerability.
6) Post-irradiation stress tests to assess latent damage, if applicable. SEGR test systems must include this capability.

B.3.5 Additional capabilities

The following features are desirable:

1) Bit error mapping and data processing, storage, and retrieval for display.
2) Ability to adjust and monitor the temperature of the DUT.
3) Latchup and/or SEB protection and monitoring capability (see 5.2.4.2 and 5.2.4.3).
4) Applicability to many device types, e.g., software control with programs written in a high-level language.
5) Speed of operation and high duty factor. Generally, a computer-assisted tester design is implied by this characteristic.
6) Real-time DUT data display capability. This capability provides a higher test throughput and allows for more precise control of testing.
7) Data reduction while tests are in progress. This feature is desirable for modification/optimization of test procedures in the light of data being acquired.
8) DUT switch system for catastrophic SEE testing. A switch system can be used to remotely switch input biases and signal output measurements to different samples mounted on a single test board. Such a system increases test efficiency by enabling multiple samples to be tested before the user must physically access the test board.

Annex C (normative) - Test figures

This annex provides figures to assist in the understanding of the test procedures in this document.

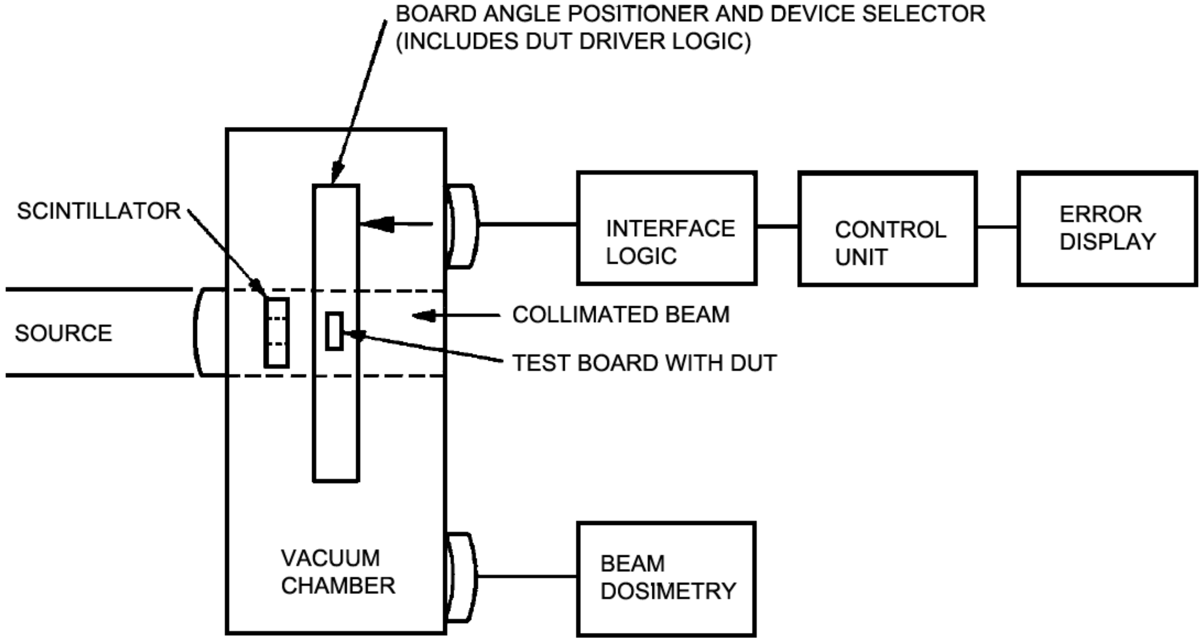


Figure C.1 — Schematic overview of SEU test

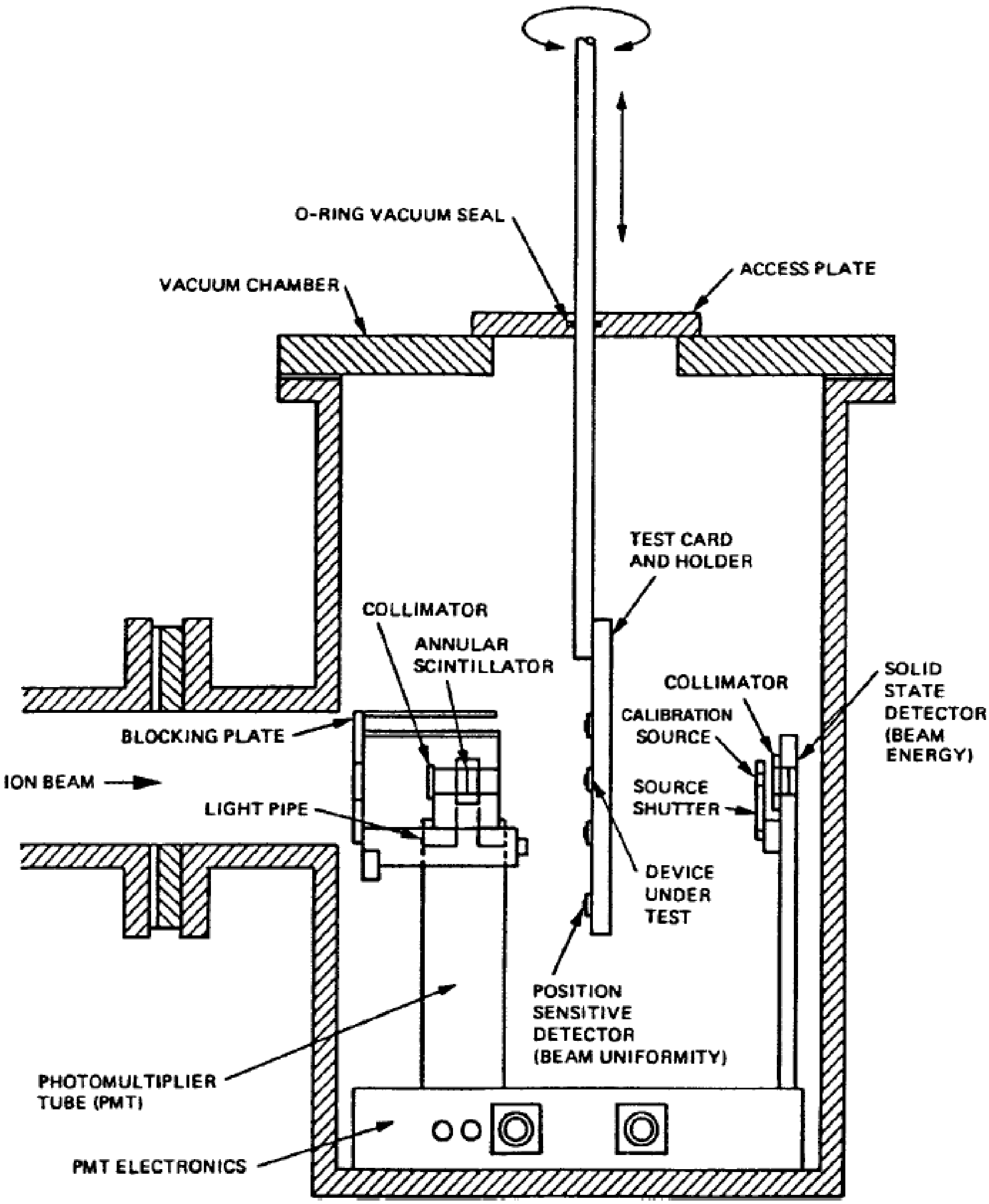


Figure C.2 — JPL Vacuum chamber

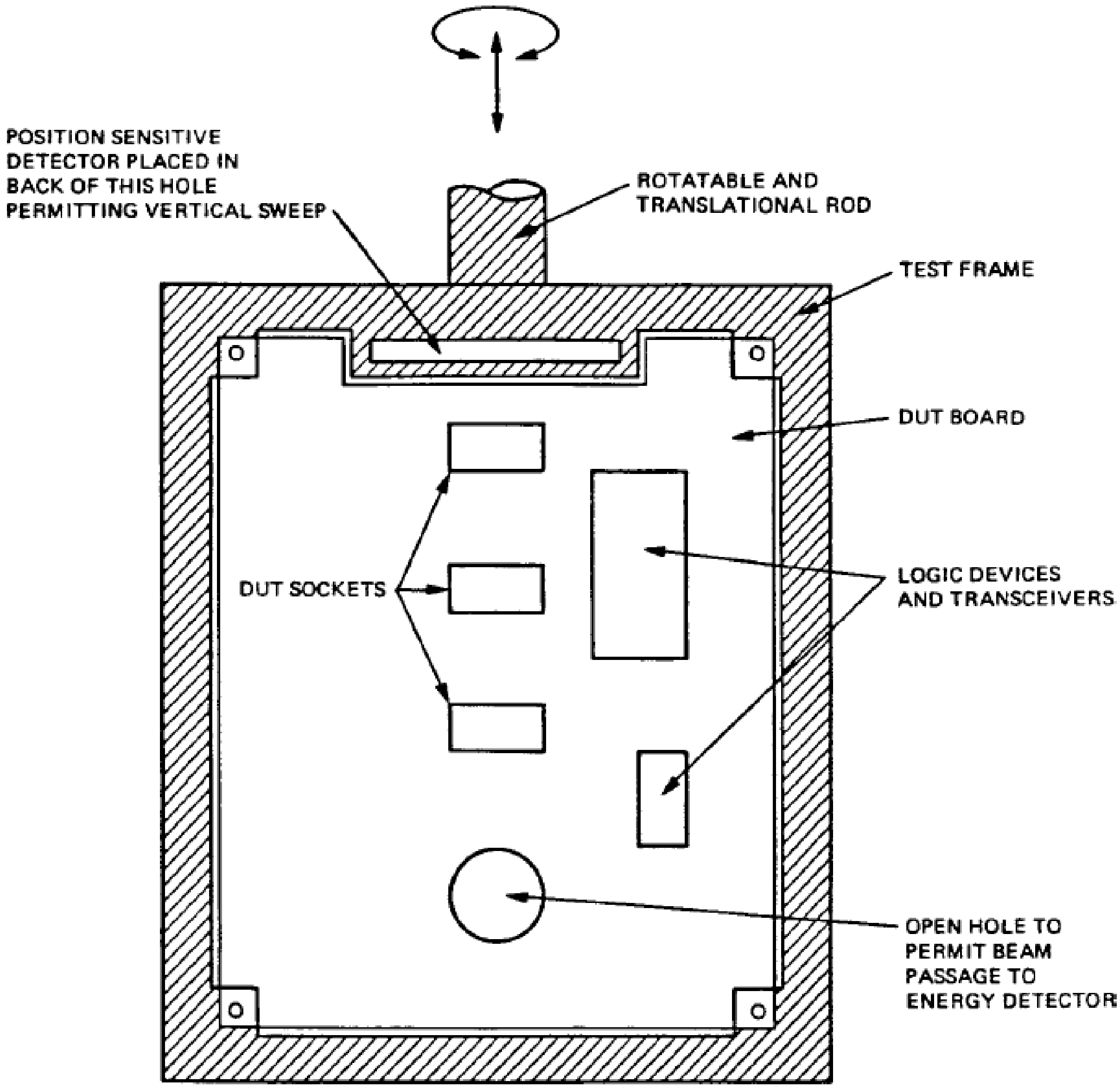


Figure C.3 — Typical DUT board (front face)

(located in vacuum chamber; connector cables lead off from rear of board)

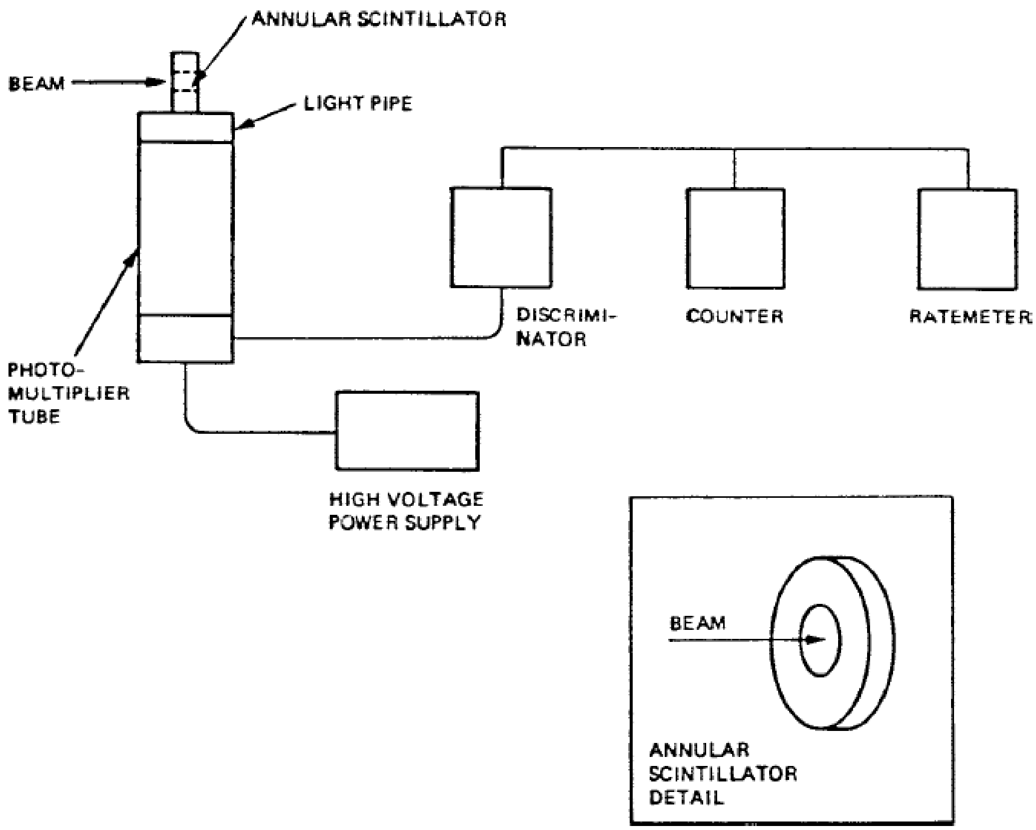


Figure C.4 — Beam measurement system

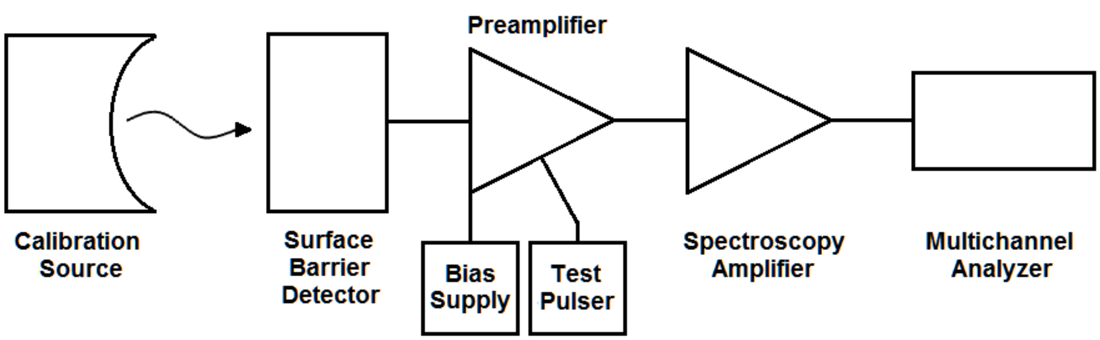


Figure C.5 — Energy measurement system

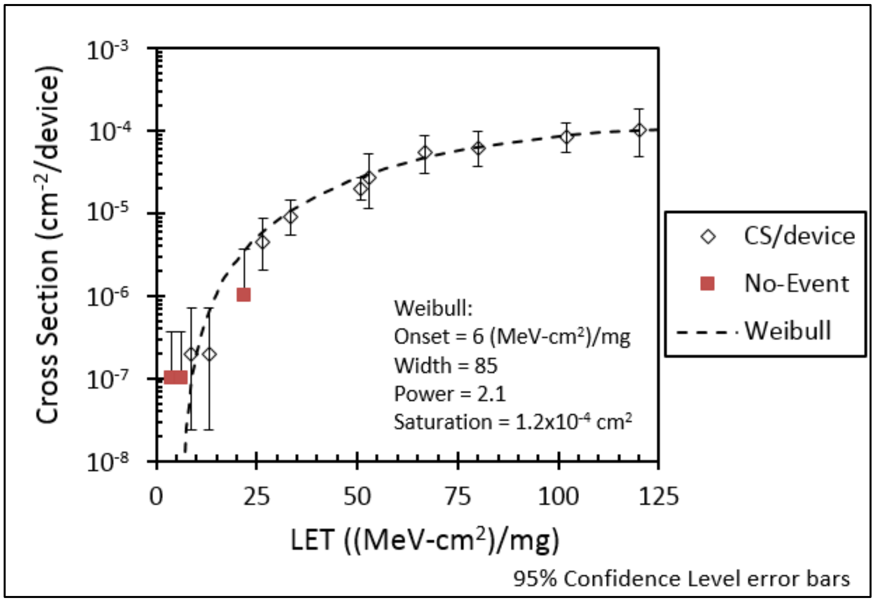


Figure C.6 — Sample cross section with cumulative Weibull distribution fit:

$$Weibull = \sigma_{sat}\left(1 - \exp\left(-\left(\frac{(LET - Onset)}{Width}\right)^{Power}\right)\right)$$

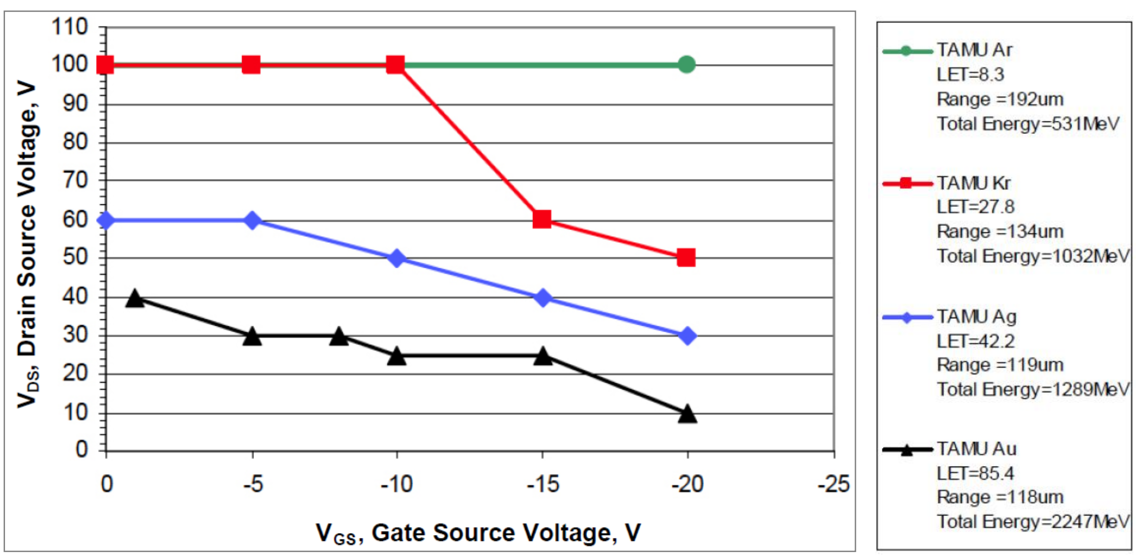


Figure C.7 — Sample off-state safe operating range as a function of ion species and energy

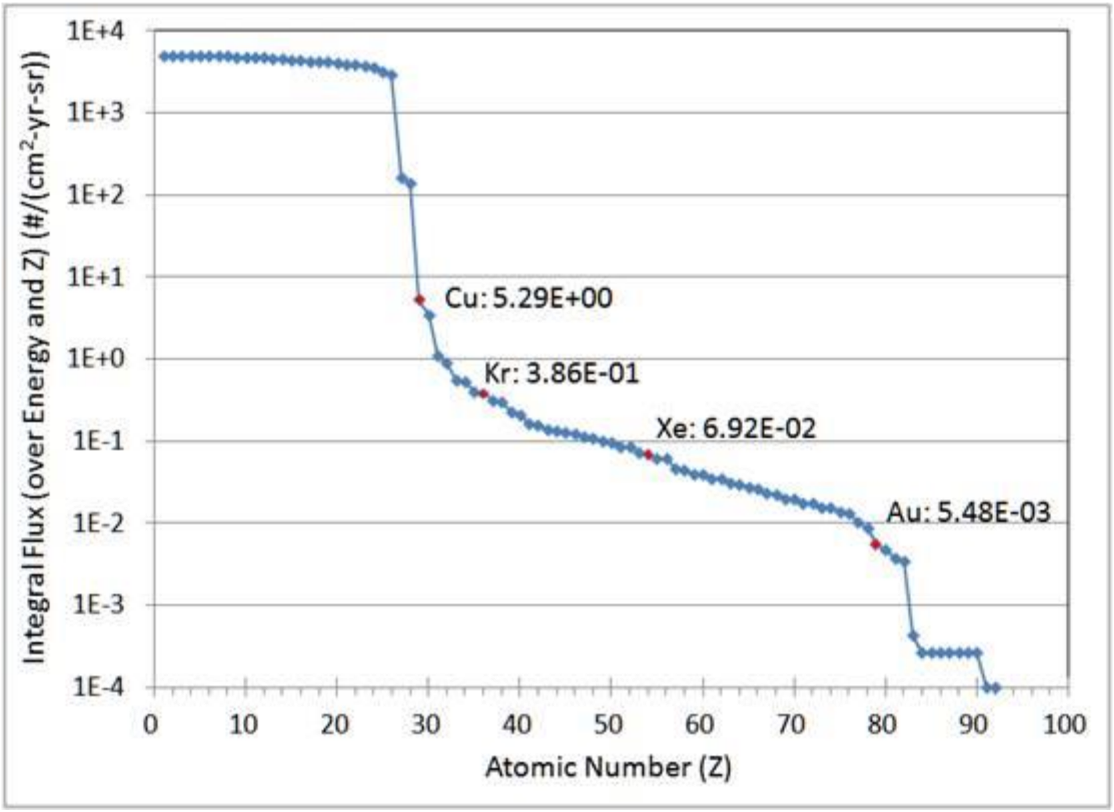


Figure C.8 — Integral ion flux versus ion species at geosynchronous orbit during solar minimum behind 100 mil Al shielding (ISO 15390 model)

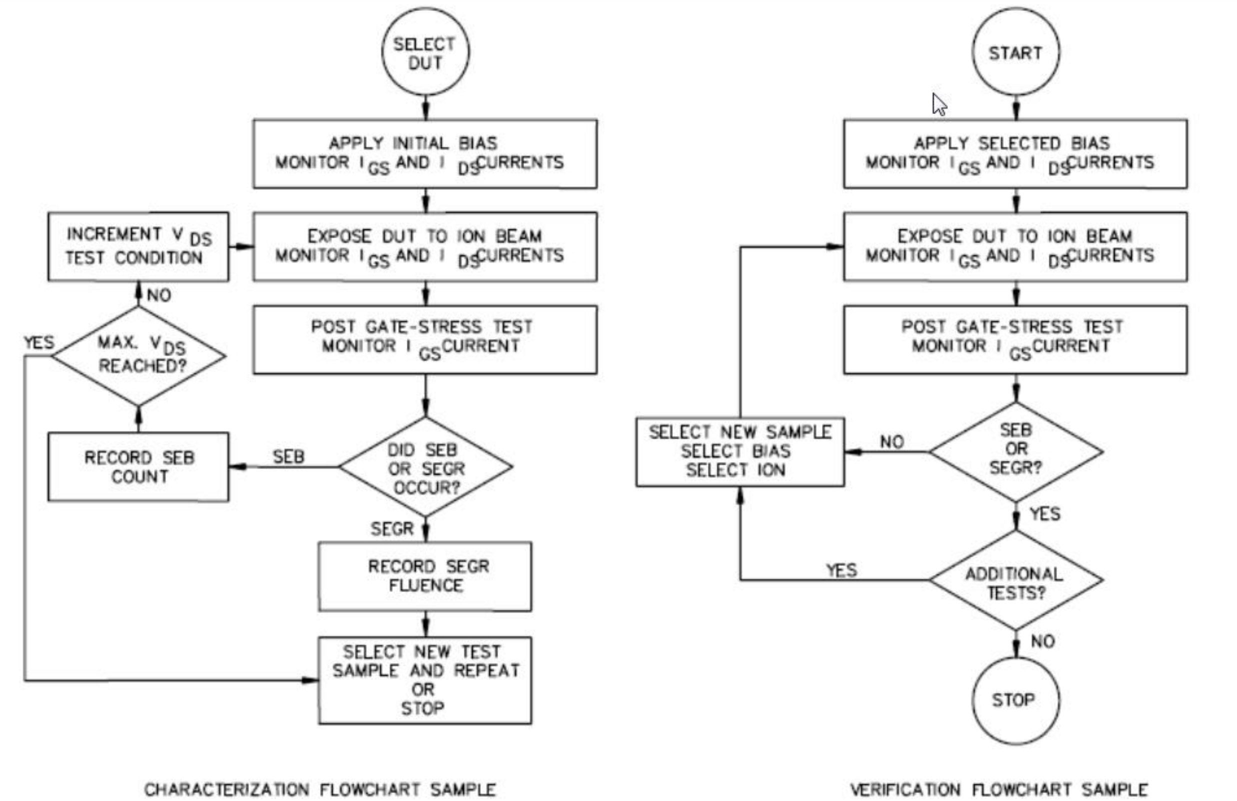
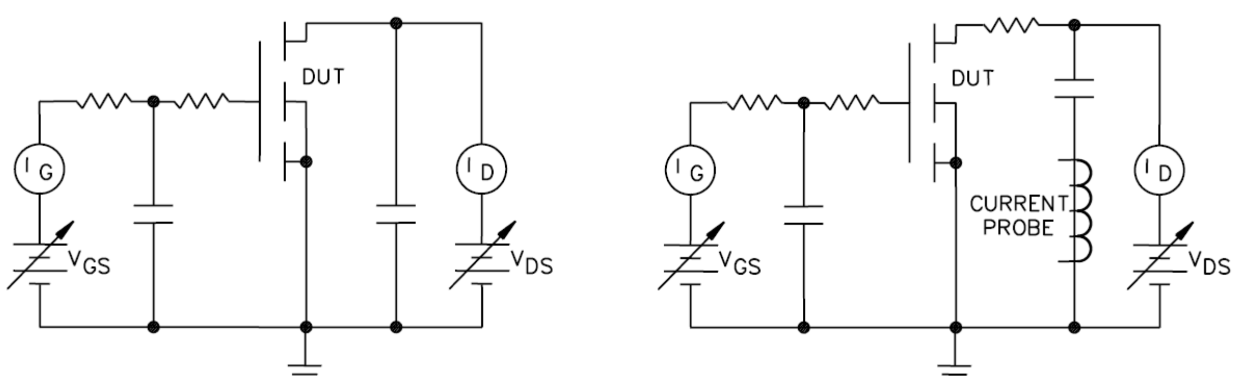


Figure C.9 — SEGR/SEB test flow diagram



a) basic SEGR/SEB test circuit **b) SEB protection and monitoring circuit**

Figure C.10 — Power MOSFET test circuit

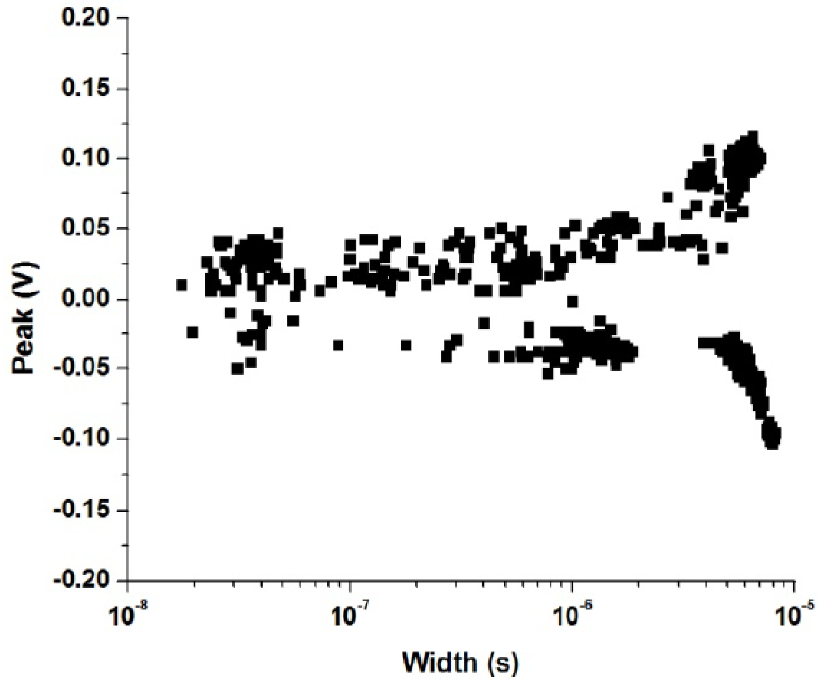


Figure C.11 — Sample plot of SET pulse characteristics

Annex D (informative) Differences between JESD57A and JESD57

This report section briefly describes the changes made to JESD57A as compared to its predecessor JESD57 (December 1996). The basis for re-writing JESD57 began with the need to update section 4.0 Single Event Gate Rupture [SEGR]; primarily because MIL-STD-750 Test Method (TM) 1080 had been re-written and released in MIL-STD-750 revision F, dated Jan. 3, 2012. Thus the goal was to align the single event gate rupture test procedures between TM 1080 and JESD57A. In the process of updating section 4.0 of JESD57, it because clear that the organization of this legacy document required a complete overhaul. The organization structure of the table of contents between the basis document [JESD57] and the revision [JESD57A] are not similar enough for a line by line comparative. The following table highlights the differences.

JESD57 [12/1996]	JESD57A	Comment
	Foreword	Introduction text added
	Section 2, Normative References	Added to revision
Section 2, Terminology	Section 3, Terms and definitions	Legacy had 17 definitions and the revision has 23 definitions, all referenced to JESD88 when possible, additional Notes provided as needed
	Section 4, Beam Dosimetry	New section added to be consistent with ASTM 1192
	Section 5, Test Plan	New section added for clarity on defining a test
	Section 6, Pre-test Procedures	New section added for guidance on a check list prior to arriving at facility
Section 4 SEGR	Within section 7	SEGR procedure re-written and moved to section 7, Test Procedures
References	Section 9 References	6 new references added
Annex A	Annex B	Equipment moved to ANNEX B
Annex B	Annex A	Interferences moved to ANNEX A
	[new] Annex D	Document revision change

Standard Improvement Form JEDEC JESD57A

The purpose of this form is to provide the Technical Committees of JEDEC with input from the industry regarding usage of the subject standard. Individuals or companies are invited to submit comments to JEDEC. All comments will be collected and dispersed to the appropriate committee(s).

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1. I recommend changes to the following:
   - ☐ Requirement, clause number ________
   - ☐ Test method number ________ Clause number ________

   The referenced clause number has proven to be:
   - ☐ Unclear ☐ Too Rigid ☐ In Error
   - ☐ Other ________

2. Recommendations for correction:

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3. Other suggestions for document improvement:

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Name: ________ Phone: ________

Company: ________ E-mail: ________

Address: ________

City/State/Zip: ________ Date: ________

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