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

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

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

**(From Council Ballot JCB-96-05 formulated under the cognizance of JC-13.4 Committee on Radiation Hardness: Assurance and Characterization.)**

### **1 Scope and purpose**

#### **1.1 Guideline**

This test method defines the requirements and procedures for Earth-based single-event effects (SEE) testing of integrated circuits.

#### **1.2 Test facility**

This test method is valid only when using a Van de Graaff or cyclotron accelerator. A test method for a Cf-252 source or a relativistic heavy ion source (e.g.  $> 10$  MeV/amu) is not included. This test method also assumes that the accelerator test facilities have the ability to mount and position the device under test (DUT) in a vacuum chamber, provide heavy ion dosimetry; measure total ionizing dose and that the testing organization has the equipment for performing these tests.

Testing may be done at facilities that do not require lid removal. These facilities use ions of high enough energy so that mounting and positioning can be done in air and without the vacuum limitation. The effect of the short air path to the device must be checked to ensure the measurement is not compromised.

#### **1.3 Basic effects addressed**

SEE includes any manifestation of soft or hard errors induced by a single ion strike. This would include single-event upset (SEU), multiple bit upset, transients that may introduce a soft error in nearby circuits, single-event gate rupture (SEGR), latchup (SEL), burnout (SEB), and single-event functional interrupt (SEFI).

#### **1.4 Limits of the test method**

This test method does not apply to SEE testing that uses neutrons, protons and other lighter particles.

### 1.5 Goal of SEE testing

For SEU and SEL, the end product of the test is a plot of the SEE cross-section vs. effective LET (linear energy transfer). This plot should extend from the threshold LET (onset of upset or latch-up) to the maximum cross-section that can be obtained. This data can be combined with the predicted heavy ion environment of the intended space application in order to predict an expected SEE rate for the DUT. For SEB and SEGR the end product is to establish safe operation limits.

### 1.6 Warnings

These tests may involve hazardous materials, operations and equipment. 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 accelerators personnel to establish the appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

### 1.7 Interferences

Annex B of this document should be reviewed before initiating SEE Testing.

## 2 Terminology

### 2.1 Critical charge (Q<sub>c</sub>)

The minimum amount of charge collected at a sensitive node due to an ion or charge particle strike that results in SEE.

### 2.2 Cross-section

The number of events per unit fluence.

NOTE – If one can assume that the depth of the sensitive volume is small compared to its lateral dimensions the SEE cross section ( $\sigma$ ) can be calculated as follows:

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

where  $\theta$  = angle of the beam with respect to the perpendicular of the chip's surface. The recommended cross-section units are  $\text{cm}^2/\text{device}$  or  $\text{um}^2/\text{bit}$ . 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. If the thin region assumption is violated, the cosine dependence assumption is no longer valid. Many modern devices violate the above stated conditions, and the experimenter must determine the applicability of the above equation to the experiment. A modification of the above equation may be necessary if the assumed conditions are violated.

### 2.3 DUT

Device Under Test.

### 2.4 Effective LET (also see LET, 2.8)

LET modified to account for the change in path length of an ion through a sensitive volume when the angle of incidence of the ion is not normal to the surface.

NOTE – Frequently, the cosine dependence is utilized for this correction. Caution must be utilized; see annex B.

$$LET(\theta) = \frac{LET(0^\circ)}{\cos \theta}$$

Many modern devices do not follow the above equation and the experimenter may have to determine the LET ( $\theta$ ) from the geometry of this particular device.

### 2.5 Fluence

The ion flux integrated over the time required for the run, expressed as  $\text{ions}/\text{cm}^2$ .

### 2.6 Flux

The number of ions passing through a one  $\text{cm}^2$  area, perpendicular to the beam, per unit time ( $\text{ions}/\text{cm}^2 \cdot \text{s}$ ).

## 2.7 Single-event (SEH) hard error

An unalterable change of operation that is typically associated with permanent damage to one or more of the device elements (e.g., gate oxide).

## 2.8 Linear energy transfer (LET)

The amount of energy lost, per unit length, as the ion travels through a material.

NOTE – The most common LET unit is  $\text{MeV}/(\text{mg}/\text{cm}^2)$ . An ion with a LET of 98  $\text{MeV}/(\text{mg}/\text{cm}^2)$  duces 1 pC of charge for each micrometer traveled in silicon. The beam deposition must be uniform through the deposition region of interest, i.e.,  $dE/dx$  is constant where E is the energy of the ion.

## 2.9 Saturated or limiting cross-section

The maximum observable cross-section.

NOTE – On many softer devices, the saturated cross-section appears as the asymptotic upper section of the LET vs cross-section curve. An additional increase in LET will not increase the cross-section of the device. On harder devices, the cross-section may not reach saturation.

## 2.10 Sensitive volume

A region, or multiple regions, of a device from which deposited charge can be collected, in such a manner as to produce SEE.

## 2.11 Single-event burnout (SEB)

A single-ion-induced condition that results in the destruction of the device due to the activation of a localized high current state that results in catastrophic failure.

## 2.12 Single-event effects (SEE)

The measurable effect in semiconductor devices due to single-event phenomena and includes SEU, multiple bit SEU, SEB, SEL, SEH and SEGR and SEFI (Single-Event Functional Interrupt).

### 2.13 Single-event functional interrupt (SEFI)

The loss of functionality of the device that does not require cycling of the device's power to restore operability unlike SEL and does not result in permanent damage as in SEB.

NOTE – SEFI is typically caused by a device being cycled to a nongenerational test mode due to a heavy ion strike.

### 2.14 Single-event gate rupture (SEGR)

A single-ion induced condition in a MOSFET that results in a breakdown and subsequent conducting path through the gate oxide.

NOTE – It is manifested by an increase in gate leakage current and can result in either the degradation or complete failure of an IC. Typically only applicable to MOSFET devices which operate using ( $V_{dc} > 5$  V) voltages such as power DMOS or EPROMs.

### 2.15 Single-event latchup (SEL)

A loss of device functionality due to a single-event.

NOTE – It may be manifested by a high current density state that may cause permanent damage to the device. If permanent damage is not sustained, power cycling of the device (off and back on) is necessary to restore normal operations. SEL is the result of a parasitic SCR structure in an IC becoming energized by an ion strike.

### 2.16 Single-event upset (SEU)

A single latched logic state from one to zero, or vice versa.

NOTE – The SEU is "soft" because the latch can be rewritten and behaves normally thereafter.

### 2.17 Threshold LET

The minimum LET required to cause a SEE.

NOTE – This minimum value may depend upon the maximum fluence utilized and may be difficult to accurately determine.

### **3 Procedures**

#### **3.1 Test plan**

##### **3.1.1 Guideline**

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 must be factored into later decisions.

##### **3.1.2 Test plan preparation**

All of the following information should be considered when writing the test plan.

###### **3.1.2.1 LET range**

LET is a fundamental measurement variable. A full device characterization usually requires irradiation with several beams of different LET to determine the upset threshold, saturated cross-section and shape of the curve between threshold and saturated value. Obtaining a range of LET values requires using different ion species, ion energies, and/or different beam angles. The beam angle is normally limited to a maximum of 60 degrees and the ion range must be linear through the region of charge collection (sensitive volume). Changing the angle to change the effective LET is useful for SEU and possibly SEE but it should not be used for SEB or SEGR. The concepts of effective LET, cross-section, and beam angles do not apply to SEB or SEGR.

###### **3.1.2.2 Beam characteristics**

The species and characteristics of the heavy ion source to be used (see 3.2.4).

###### **3.1.2.3 Operating conditions**

The description of the program(s) test procedures, device configuration, electrical bias, stimulus inputs, temperatures, current limiting conditions, clock rate, reset conditions, etc., must be established. As a general rule, the worst case test condition for upset is at minimum operating voltage. The worst case test condition for latchup is maximum operating voltage and maximum operating temperature. However, actual "worst-case" conditions should be ascertained for each device type.