Standard Guide for Transient Radiation Upset Threshold Testing of Digital Integrated Circuits [Metric][1]

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1. Scope

1.1 This guide is to assist experimenters in measuring the transient radiation upset threshold of silicon digital integrated circuits exposed to pulses of ionizing radiation greater than 10^3 Gy (Si)/s.

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

2. Referenced Documents

2.1 *ASTM Standards:*

E 666 Practice for Calculating Absorbed Dose from Gamma or X Radiation[2]

E 668 Practice for the Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices[2]

F 867M Guide for Ionizing Radiation Effects (Total Dose) Testing of Semiconductor Devices [Metric][3]

2.2 *Military Standards:* [4]

Method 1019 in MIL-STD-883. Steady-State Total Dose Irradiation Procedure

Method 1021 in MIL-STD-883. Dose Rate Threshold for Upset of Digital Microcircuits.

3. Terminology

3.1 *Definitions:*

3.1.1 *combinational logic*—A digital logic system with the property that its output state at a given time is solely determined by the logic signals at its inputs at the same time (except for small time delays caused by the propagation delay of internal logic elements).

3.1.1.1 *Discussion*—Combinational circuits contain no internal storage elements. Hence, the output signals are not a function of any signals that occurred at past times. Examples of combinational circuits include gates, adders, multiplexers and decoders.

3.1.2 *complex circuit response mechanisms*—For medium scale integration (MSI) and higher devices it is useful to define three different categories of devices in terms of their internal design and radiation response mechanisms.

3.1.3 *over-stressed device*—A device that has conducted more than the manufacturer's specified maximum current, or dissipated more than the manufacturer's specified maximum power.

3.1.3.1 *Discussion*—In this case the DUT is considered to be overstressed even if it still meets all of the manufacturer's specifications. Because of the overstress, the device should be evaluated before using it in any high reliability application.

3.1.4 *sequential logic*—A digital logic system with the property that its output state at a given time depends on the sequence and time relationship of logic signals that were previously applied to its inputs.

3.1.4.1 *Discussion*—Examples of sequential logic circuits include flip-flops, shift registers, counters, and arithmetic logic units.

3.1.5 *state vector*—A state vector completely specifies the logic condition of all elements within a logic circuit.

3.1.5.1 *Discussion*—For combinational circuits, the state vector includes the logic signals that are applied to all inputs: for sequential circuits, the state vector must also include the sequence and time relationship of all input signals. In this guide the output states will also be considered part of the state vector definition. For example, an elementary 4-input NAND gate has 16 possible state vectors, 15 of which result in the same output condition ("1" state). A 4-bit counter has 16 possible output conditions, but many more state vectors because of its dependence on the dynamic relationship of various input signals.

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[2] *Annual Book of ASTM Standards*, Vol 12.02.

[3] Discontinued. Replaced by F 1893. See 1997 *Annual Book of ASTM Standards*, Vol 10.04.

[4] Available from Standardization Documents Order Desk, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

3.1.6 *upset response*—The electrical response of a circuit when it is exposed to a pulse of transient ionizing radiation.

3.1.6.1 *Discussion*—Two types of upset response can occur:

(1) transient output error, for which the instantaneous output voltage of an operating digital circuit is greater than a predetermined value (for a low output condition) or less than a predetermined value (for a high output condition), and the circuit spontaneously recovers to its pre-irradiation condition after the radiation pulse subsides. The predetermined values mentioned above are agreed to by all parties participating in the test and should be included in the test plan.

(2) stored logic state error, for which there is a change in the state of one or more internal logic elements that does not recover spontaneously after the radiation pulse. Because the radiation changes the state vector, the circuit spontaneously recovers to a different logic state. This does not imply the change will always be immediately observable on a circuit output. However, the circuit can be restored to its original state vector by re-initializing it afterwards.

3.1.6.2 *Discussion*—Although the term upset response is usually used to describe output voltage responses, some devices, such as open collector gates, are better characterized by measuring the output current. Upset response also includes the transient currents that are induced in the power supply leads (sometimes very large) as well as the response of the device inputs, although in most applications the input response is not significant.

4. Summary of Guide

4.1 For transient radiation upset threshold tests, the transient output voltage and the condition of internal storage elements, or both, is measured at a succession of radiation levels to determine the radiation level for which transient voltage or functional test errors first occur. An oscilloscope, digital storage oscilloscope, transient digitizer or similar instrument is used to measure the output transient voltage. Functional tests are made immediately after irradiation to detect internal changes in state induced by the radiation. The device is initially biased and set up in a predetermined condition. The test conditions are determined from topological analyses or by testing the device in all possible logic state combinations.

4.2 A number of factors are not defined in this guide and must be agreed upon beforehand by the parties to the test. These factors are described in the test plan. As a minimum the test plan must specify the following:

(*1*) Pulse width, energy spectrum, and type of radiation source,

(*2*) Voltage and electrical loading conditions on each pin of the device during testing,

(*3*) Resolution and accuracy required for the upset response threshold of individual devices, along with the method used to vary the radiation level,

(*4*) Failure criterion for transient voltage upset, output current, and power supply current as applicable,

(*5*) Measuring and reporting I_{pp}, transient output voltage and transient output current levels,

(*6*) Functional test to be made after irradiation,

(*7*) Power supply and operating frequency requirements,

(*8*) State vectors used for testing,

(*9*) Radiation levels to use for transient response measurements,

(*10*) Recommended radiation level at which to begin the test sequence, and

(*11*) Procedure to adjust the dose rate during testing.

(*12*) Device temperature during test.

4.3 The state vectors in which the device is to be irradiated are determined from the basic (see 8.2.1) and topological analysis, (see 8.2.2) or both.

5. Significance and Use

5.1 Digital logic circuits are used in system applications where they are exposed to pulses of radiation. It is important to know the minimum radiation level at which transient failures can be induced, since this affects system operation.

6. Interferences

6.1 *Accumulated Ionizing Dose*—Many devices may be permanently damaged by the accumulated ionizing dose they are exposed to during upset testing. This limits the number of radiation pulses that can be applied during transient upset testing. Accumulated ionizing dose sensitivity depends on fabrication techniques and device technology. Metal oxide semiconductor (MOS) devices are especially sensitive to accumulated ionizing dose damage. Newer bipolar devices with oxide-isolated sidewalls may also be affected by low levels of accumulated ionizing dose. The maximum ionizing dose to which devices are exposed must not exceed 10 % (see 8.4.5) of the typical ionizing dose failure level of the specific part type.

6.2 *Dosimetry Accuracy*—Since this guide ultimately determines the dose rate at which upset occurs, dosimetry accuracy inherently limits the accuracy of the guide.

6.3 *Latchup*—Some types of integrated circuits may be driven into a latchup condition by transient radiation. If latchup occurs, the device will not function properly until power is temporarily removed and reapplied. Permanent damage may also occur. Although latchup is an important transient response mechanism, this procedure is not applicable to latchup testing. Functional testing after irradiation is required to detect internal changes of state, and this will also detect latchup.

6.4 *Package Response*—At dose rates above 10^8 Gy (Si)/s the response may be dominated by the package response rather than the response of the integrated circuit device being tested. For high speed devices, this may include lead/bondwire effects with upsets caused solely by the radiation pulse's rise and fall rates rather than dose rate. Package effects can be minimized by adequately decoupling the power supply with appropriate high-speed capacitors.

6.5 *Steps Between Radiation Levels*—The size of the steps between successive radiation levels limits the accuracy with which the dose rate upset threshold is determined. Cost considerations and ionizing dose damage limit the number of radiation levels that can be used to test a given device.

6.6 *Limited Number of State Vectors*—Cost, testing time, and cumulative ionizing radiation usually make it necessary to restrict upset testing to a small number of state vectors. These state vectors must include the most sensitive conditions in order to avoid misleading results. An analysis is required to select the state vectors used for radiation testing to make sure that circuit and geometrical factors that affect the upset response are taken into account.

7. Apparatus

7.1 The equipment and information required for this guide includes an electrical schematic of the test circuit, a logic diagram of the device to be tested, a transient radiation simulation source, dosimetry equipment, and electrical equipment for the measurement of the device response and functional testing. If the alternate topological analysis approach is to be used, (see 8.2.2) then a photomicrograph or composite mask drawing of the device is also needed.

7.2 *Radiation Simulation and Dosimetry Apparatus*:

7.2.1 *Transient Radiation Source*—A pulsed high energy electron or bremsstrahlung source that can provide a dose rate in excess of the upset response threshold level of the device being tested at the pulse width specified in the test plan is needed. A linear accelerator (LINAC) with electron energies of 10 to 25 MeV is preferred (see Note 1), although in some instances a flash X ray with end point energy above 2.0 MeV may be utilized (see Note 2 and Note 3). It is usually much more difficult to synchronize a flash X-ray pulse with circuit operation, which limits the applicability of a flash X ray.

NOTE 1—Linac radiation pulses are made from a train of discrete "micropulses" occurring at the linac radio frequency (RF). This high frequency pulse structure could cause erroneous results for high frequency devices under test such as gallium arsenide. This has not yet been directly observed.

NOTE 2—The absorption coefficient of photons in silicon and packaging materials is relatively flat at energies above 2 MeV, and has a nearly constant ratio to the absorption coefficient of typical dosimetry systems. At lower energies absorption coefficients increase, which can introduce large dosimetry errors if the end point energy in a bremsstrahlung source is below 2.0 MeV.

NOTE 3—Because of dose enhancement and attenuation, a transport calculation is generally required to relate the dose at the region of interest in the DUT to the dosimetry used if a low energy flash X ray is used.

7.2.2 *Ionizing Dose Dosimetry System*—A dosimetry system such as a thermoluminescent dosimetry (TLD) system or calorimeter that can be used to measure the absorbed ionizing dose produced by a single pulse of the radiation source is needed (see Practice E 668).

7.2.3 *Pulse Shape Monitor*—A device for monitoring the shape of the radiation pulse such as a PIN diode is required. In some instances it may be possible to directly determine the pulse shape by measuring the total beam current of the accelerator with a current transformer or secondary emission monitor (SEM).

7.2.4 *Active Dosimetry Standard*—An active dosimeter that allows the dose rate to be determined from electronic measurements is needed. This may be a PIN detector, a Faraday cup, or a combination of a calorimeter and current transformer.

7.3 *Electronic Test Equipment*:

7.3.1 *Radiation Test Fixture*—A test fixture that allows the device to be placed in the radiation beam with convenient connection to external equipment (pulse generators, power supplies, line drivers etc.) is required for testing.

7.3.2 *Line Drivers*—Line drivers that provide high impedance to the device under test and can drive the low impedance of terminated output cables with adequate signal fidelity are required. The line drivers must be designed so that their own response to transient ionizing radiation is much smaller than that of the circuit being measured (see Note 4).

NOTE 4—Although line drivers are normally not placed in the direct radiation beam, there is always some stray radiation that may affect the line driver. Furthermore, replacement currents in the wiring that connects the line driver to the circuit under test may also introduce a spurious response.

7.3.3 *General Purpose Test Equipment*—Power supplies, pulse generators, cables and termination resistors that are required to bias the device and establish its internal operating conditions are needed.

7.3.4 *Transient Response Measuring Device*—An oscilloscope, transient digitizer or similar device shall be used to measure the transient response of the device under test. The bandwidth and sensitivity of this equipment must be compatible with the pulse width and measurement criteria in the test plan.

7.3.5 *Functional Test System*—A system that is set up to test the functional operation of the device under test while it is in the radiation test fixture is required. This may consist of (*1*) general purpose equipment such as pulse generators, oscilloscopes/transient digitizers, or logic analyzers, (*2*) a commercial integrated circuit test system, or (*3*) a custom test circuit/fixture. The specific requirements of the functional test system depend on the specifications and requirements of the device under test and are included in the test plan.

7.3.6 *Temperature Measuring Equipment*—A thermometer, calorimeter, or other temperature measuring device that can measure the ambient temperature with an accuracy of at least ±3°C.

8. Procedure

8.1 The procedure will be governed by the test plan that describes the device operating conditions, upset response criteria, functional test method, and radiation source requirements. The procedure is divided into three parts: (*1*) determination of the logic state conditions for testing by analysis using either the device schematic or the alternate topological analysis: (*2*) calibration and adjustment of the radiation facility; and (*3*) measurement of the radiation level at which transient upset occurs. The state vectors selected for irradiation are determined from the analysis step.

8.1.1 The test results are incorporated into a test report that includes necessary information about the test sample and measurement conditions as well as the test data.

8.2 *Analysis*:

(*a*) The purpose of the analysis step is to select the minimum number of state vectors for transient response testing. The device must be tested in each of these logic states, and must include the conditions in which the analysis shows that the device is most sensitive to transient upset.

(*b*) The analysis starts with a schematic diagram and circuit operating description such as bias conditions, timing diagram etc. If the alternate approach of topological analysis is used, then a photomicrograph or composite mask drawing is also required. It is assumed that the basic response mechanisms of the device technology are known from experience or test data on small scale logic circuits that are fabricated with the same technology. Specific steps in the analysis are listed as follows:

8.2.1 *Multiple Output Logic State Approach*:

8.2.1.1 *Determine Relative Response Sensitivity*—Partition the circuit into functional logic blocks. Determine the logic path for each output, and identify similar internal functions. For example, a 4-bit counter can be separated into control, internal flip-flop, and output logic cells. There are four identical logic paths corresponding to each of the four bits. Determine the total number of unique output logic state combinations, and test the circuit in each of these states. For the counter example this results in 16 combinations so that the upset must be determined for each of these 16 state vectors.

8.2.2 *Topological Analysis Approach (Alternate)*:

8.2.2.1 Partition the circuit into functional logic blocks. Determine the logic paths for each output and identify similar functions. Measure the relative junction areas of transistors in each logic path. For example, in bipolar devices that respond because of substrate photocurrent, the area of the isolation diffusion is measured, whereas for devices that respond because of secondary photocurrent, the collector-base junction area is measured. In MOS technology devices the areas of the *p*- or *n*-wells and the areas of specific transistors must be determined.

8.2.2.2 Assume the photocurrent at a specific radiation level is proportional to junction area. Use nominal resistor values to determine the relative voltage drop (and hence the relative upset level) of each functional block in the logic path. This step will identify the logic element that has the highest sensitivity to radiation for each logic path. This step also determines which internal logic state is most sensitive to transient ionizing radiation pulses.

8.2.2.3 *Identification of Asymmetries and Parasitic Junctions*—Carefully examine the geometry of functionally similar logic paths to determine if any asymmetries exist that would cause specific locations to be more sensitive to upset. In order for such differences to be significant, there must be an obvious difference in junction areas. Also examine the layout to check for differences in proximity to other elements between functionally identical logic cells. Make sure that regions with obvious physical differences are identified and included in the state vector set used for irradiation.

8.2.2.4 *State Vector Selection*—Use the results of the functional block analysis and topological analysis to select state vectors and monitor points that correspond to the most sensitive logic cells. The topological analysis will generally result in a much smaller number of state vectors than the multiple logic state approach.

8.2.3 *Test Plan Modification*:

8.2.3.1 Use the results of the preceding steps to incorporate the test vectors selected in 8.2.1 or 8.2.2 into the test plan. The total number of state vectors selected for radiation testing must be compatible with cost and ionizing dose limitations.

8.3 *Set Up and Calibration of the Radiation Facility*:

8.3.1 *Accelerator Set Up*—Adjust the accelerator to the energy, pulse width and nominal intensity specified in the test plan. Verify that the beam area and uniformity are adequate for the device being tested and the placement of the active dosimeter.

8.3.2 *Calibration*—Measure the ionizing dose and pulse width of the accelerator, using the thermoluminescent dosimeter (TLD) or calorimeter and an appropriate pulse shape monitor. Practices E 666 and E 668 provide appropriate test methods. The maximum tolerance specified in Practices E 666 and E 668 is the maximum tolerance allowed by this guide.

8.3.3 *Active Dosimeter Calibration*—Calibrate the active dosimeter using the same methods. Verify that the active dosimeter has a linear response over the expected range of radiation levels.

8.3.4 *Noise Test*—Set up the radiation test fixture. Place small dummy load resistors on each active pin of the test fixture that are nominally equal to the active impedance of each pin of the device (electrical measurements or circuit analysis can be used to determine the appropriate load impedances). Irradiate the test fixture and dummy loads and measure the output response. This response must be less than ⅓ of the output response that constitutes transient failure (see the test plan 7.1).

8.4 *Radiation Testing*:

8.4.1 *Sample Selection*—Specify the number of devices to be tested in the test plan. Randomly select the test samples from the parent population (unless otherwise specified). The test samples must be fabricated with the same mask set used in the analysis (8.2). Identify each part individually with a serial number. For devices that are sensitive to damage from static discharge, use appropriate handling methods. In addition to the test devices, select a minimum of two expendable devices from the test sample for use in setting up the functional test and transient upset test equipment.

8.4.2 *Set Up and Check Out Functional Test System*—Assemble the equipment required for functional testing and adjust the wave form amplitudes and timing to the values specified in the test plan. Adjust the power supplies required for testing to the correct values and connect them to the radiation test fixture. Temporarily turn off or disconnect the power and insert one of the expendable devices in the test fixture. Reapply power and verify proper operation of the functional test system.

8.4.3 *Set Up and Check Out Upset Response Test System*—Assemble the equipment required to measure the transient response of the device (this usually includes line drivers). Terminate all coaxial cables with their characteristic impedance. Place the active dosimeter in close proximity to the device under test (the beam uniformity was previously established in 8.3.1). Place one of the expendable devices in the test fixture and set it up in one of the state vectors that were selected in 8.3. Pulse the accelerator and measure the transient response of the device and the dose rate. If the response is greater or less than that defined as logic failure adjust the accelerator for a higher or lower dose rate and repeat the test. Continue this process until the upset response level for each state vector has been bracketed.

8.4.4 *Dynamic Dose-Rate Testing Considerations*—For dynamic dose-rate testing synchronize the tester and radiation source such that the radiation pulse can be positioned at any point in time in the operating cycle of the DUT. Make sure that the test setup is capable of observing the position of the radiation test pulse with respect to the operating cycle. For test performance step the radiation test pulse through the operating cycle with overlap to identify the most sensitive (with respect to the radiation pulse) point in the operating cycle of the DUT. For dynamic testing the upset response can take several forms including a temporal change in the operating cycle.

8.4.4.1 For complex devices with operating cycles less than 1 µs, it is possible to use a LINAC pulse width which is longer than the operating cycle (~1 µs). In this case, the synchronized radiation pulse will be present during the entire operating cycle and eliminate the need to step the shorter (10 to 30 ns) radiation pulse. Of course the ionizing dose per pulse would be much larger but the total number of radiation pulses would be less.

8.4.5 *Ionizing Dose Damage Sensitivity Estimation*—Using an expendable device from 8.3 or 8.4, determine the ionizing dose from a single pulse of ionizing radiation and appropriate dosimetry. Also estimate the failure threshold of the device from other test data or similar device types of experiments. If the ionizing dose per pulse exceeds 10 % (unless otherwise specified, see 4.2) of the estimated failure threshold, then the devices shall be tested before and after dose rate testing to determine the effect of ionizing dose.

8.4.5.1 The ionizing dose damage threshold is the level at which significant degradation, typically a 10 % (unless otherwise specified, see 4.2) change in electrical parameters occurs.

8.4.6 *Ionizing Radiation Testing (Optional)*—If the results of the previous step show that cumulative ionizing radiation testing is required, then each device must be electrically characterized before and after upset response testing. This testing must be compatible with Guide F 867M. The preferred radiation source for determining a device's cumulative ionizing radiation failure threshold is ^{60}Co, however, if suitable ^{60}Co or equivalent data does not exist, then a pulsed source may be used to estimate the device's cumulative ionizing radiation failure threshold.

8.4.7 *Dose Rate Upset Threshold Measurement*—Place the device to be tested in the test socket. Apply the required pulse sequence so that the device is in the state specified by the test plan for the first state vector test.

8.4.7.1 Set the intensity of the radiation source to the initial level specified in the test plan, and expose the device to a pulse of radiation. Determine if a transient output error or a stored logic state error occurred (see 3.1.5).

8.4.7.2 If no upset occurred, increase the radiation level according to the sequence specified in the test plan: if an upset is observed decrease the radiation level. After the radiation source is adjusted to the new intensity, re-initialize the part to the required state vector, expose it to an additional pulse, and determine whether or not upset occurred. Continue this sequence until the upset response threshold level is bracketed with the resolution required in the test plan.

8.4.7.3 Repeat 8.4.7.1 and 8.4.7.2 for all the state vectors required in the test plan. Test the remaining devices in the same way starting at the best estimated radiation level in order to minimize the number of pulses required in the test sequence.

8.4.7.4 Consider a test device over-stressed and identify the device accordingly if the maximum transient photocurrent has caused the device to exceed the manufacturers specified absolute maximum DC level of current or power (see 3.1.3).

9. Calculation

9.1 For each device and state vector, determine the upset response threshold from dose rate data above and below threshold as determined with the active dosimeter. The accuracy of the result is limited by the difference between successive radiation levels that bracket the upset response threshold.

10. Report

10.1 As a minimum the report shall include the following:

10.1.1 Device identification,

10.1.2 Test date and test operator,

10.1.3 Test facility, radiation source specifications, including energy spectrum and radiation pulse width,

10.1.4 Bias conditions, output loading and test circuit,

10.1.5 Description of the way in which state vectors for testing were selected,

10.1.6 State vectors used for radiation testing and functional test conditions for each state vector,

10.1.7 Criteria for transient output upset failure and power supply current failure (if applicable),

10.1.8 Records of the upset threshold and power supply current for each state vector,

10.1.9 Equipment list,

10.1.10 Results of the noise test,

10.1.11 Device temperature during test, and

10.1.12 Restrictions on cumulated ionizing radiation.

11. Keywords

11.1 digital integrated circuits; digital IC's; functional errors; ionizing; pulsed radiation; radiation; transient radiation; upset threshold