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Guide for Measurement of Ionizing Dose-Rate Burnout of Semiconductor Devices[1]

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1. Scope

1.1 This guide defines the detailed requirements for testing microcircuits for short pulse high dose-rate ionization-induced failure. Large flash x-ray (FXR) machines operated in the photon mode, or FXR e-beam facilities are required because of the high dose-rate levels that are necessary to cause burnout. Two modes of test are possible: (*1*) A survival test, and (*2*) A failure level test.

1.2 The values stated in International System of Units (SI) are to be regarded as standard. No other units of measurement are included in this standard.

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]

3. Terminology

3.1 *Definitions:*

3.1.1 *dose rate*—energy absorbed per unit time per unit mass by a given material that is exposed to the radiation field (Gy/s, rd/s).

3.1.2 *high dose-rate burnout*—permanent damage to a semiconductor device caused by abnormally large currents flowing in junctions and resulting in a discontinuity in the normal current flow in the device.

3.1.2.1 *Discussion*—This effect strongly depends on the mode of operation and bias conditions. Temperature may also be a factor in damage to the device should latchup occur prior to failure. Latchup is known to be temperature dependent.

3.1.3 *failure condition*—a device is considered to have undergone burnout failure if the device experiences one of the following conditions.

(*1*) *functional failure*—a device failure where the device under test, (DUT) fails the pre-irradiation functional tests following exposure.

(*2*) *parametric failure*—a device failure where the device under test, DUT fails parametric measurements after exposure.

3.1.3.1 *Discussion*—Functional or parameteric failures may be caused by total ionizing dose mechanisms. See interferences for additional discussion.

3.1.4 *survival test*—A "pass/fail" test performed to determine the status of the device after being exposed to a predetermined dose-rate level. The survival test is usually considered a destructive test.

3.1.5 *burnout level test*—a test performed to determine the actual dose-rate level where the device experiences burnout.

3.1.5.1 *Discussion*—In such a test, semiconductor devices are exposed to a series of irradiations of differing dose-rate levels. The maximum dose rate at which the device survives is determined for worst-case bias conditions. The failure level test is always a destructive test.

4. Summary of Guide

4.1 Semiconductor devices are tested for burnout after exposure to high ionizing dose-rate radiation. The measurement for high-dose-rate burnout may be a survival test consisting of a pass/fail measurement at a predetermined level; or it may be a failure level test where the actual dose-rate level for burnout is determined experimentally.

4.2 The following quantities are unspecified in this guide and must be agreed upon between the parties to the test:

4.2.1 The maximum ionizing (total dose to which the devices will be exposed, and

4.2.2 The maximum high dose rate to which the devices will be exposed.

5. Significance and Use

5.1 The use of FXR radiation sources for the determination of high dose-rate burnout in semiconductor devices is addressed in this guide. The goal of this guide is to provide a systematic approach to testing for burnout.

5.2 The different type of failure modes that are possible are defined and discussed in this guide. Specifically, failure can be defined by a change in device parameters, or by a catastrophic failure of the device.

5.3 This guide can be used to determine the survivability of a device, that is, that the device survives a predetermined level; or the guide can be used to determine the survival dose-rate

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

capability of the device. However, since this latter test is destructive, the minimum dose-rate level for failure must be determined statistically.

6. Interferences

6.1 There are several interferences that need to be considered when this test procedure is applied.

6.2 *Ionizing Dose Damage*—Devices may be permanently damaged by the accumulation of ionizing dose. This limits the number of radiation pulses that can be applied during burnout testing. The ionizing dose sensitivity depends on fabrication techniques and device technology. Metal oxide, semiconductor (MOS) devices are especially sensitive to ionizing dose damage, however, bipolar devices with oxide-isolated sidewalls may also be affected by low levels of ionizing dose. The maximum ionizing total dose exposure of the test devices must not exceed fifty percent (50 %) of the typical ionizing dose failure level of the specific part type to ensure that a device failure is caused by burnout, and not by an ionizing total dose.

6.2.1 *Radiation Level Step Size*—The size of the steps between successive radiation levels limits the accuracy of the determination of the burnout failure level.

6.3 *Latchup*—Some types of integrated circuits are susceptible to latchup during transient radiation exposure. If latchup occurs, the device will not function correctly until power is temporarily removed and reapplied. Permanent damage (burnout) may also occur during latchup, primarily caused by a substantial increase in power supply current that leads to increased power dissipation, localized heating, or both. Latchup is temperature dependent and testing at elevated temperature is required to establish worst-case operating conditions for latchup. Latchup testing is addressed elsewhere.

6.4 *Charge Build-up Damage*—Damage to a device may occur due to direct electron irradiation of the DUT leads. When using direct electron irradiation of the DUT leads. When using direct electron irradiations, (see Section 7), all device leads must be shielded from the electron beam to reduce charge pickup that could cause abnormally large voltages to be generated on internal circuitry and produce damage not related to ionizing dose-rate burnout.

6.5 *Bias and Load Conditions*—The objective of the test is to determine the dose-rate survivability of the test devices when tested under worst case conditions.

6.5.1 *Input Bias*—Unless otherwise specified, the input bias condition shall be chosen to provide the worst-case operating conditions. For example, for digital devices, input pins that are in the high state should be tied directly to the supply voltage. For analog devices, input voltages generally should be at the maximum levels expected to be used. For both digital and analog devices, it is desirable to perform the burnout test using at least two different input conditions, such as minimum input levels and maximum input levels, or alternately with half the inputs tied high and the remaining tied low.

6.5.2 *Output Loading*—Unless otherwise specified, the DUT outputs shall be chosen to provide the worst-case conditions for device operation. For digital devices, worst case conditions should include maximum fan-out. For analog devices, worst-case conditions should include maximum output voltage or load current. For both digital and analog devices, it may be desirable to perform the burnout test using at least two different output conditions.

6.5.3 *Operating Voltage*—Unless otherwise specified, testing shall be performed using maximum operating voltages. The test setup shall be configured such that the transient power supply photocurrent shall not be limited by the external circuit resistance or lead inductance. Power supply stiffening capacitors shall be included to keep the power supply voltage from varying more than 10 % of the specified value during and after the radiation pulse.

6.6 *Over-Stress*—The high dose-rate burnout test should be considered destructive. Peak photocurrents in excess of 2 to 3 amperes can occur during these tests. These large currents can produce localized metalization, or semiconductor melting that is not readily detected by electrical testing, or both, but may adversely affect device reliability. Devices that exceed manufacturer's absolute limits for current or power during burnout testing should not be used in high-reliability applications.

6.7 *Test Temperatures*—Testing shall be performed at ambient temperature, or at a temperature agreed upon between the parties to the test. If testing is performed in a vacuum, overheating may be an issue, and temperature control is required.

7. Apparatus

7.1 *General*—The apparatus used for testing should include as a minimum, the radiation source, dosimetry equipment, a test circuit board, line drivers, cables and electrical instrumentation to measure the transient response, provide bias, and perform functional tests. Precautions shall be observed to obtain an electrical measurement system with ample shielding, satisfactory grounding, and low noise from electrical interference or from the radiation environment.

7.1.1 *Radiation Source*—The most appropriate radiation source for high dose-rate burnout testing is a FXR machine. The required dose rate for burnout cannot usually be achieved using an electron linear accelerator (LINAC) because LINACs typically cannot produce a sufficiently high dose rate over the critical active area of the device under test. Linear accelerators shall be used only with agreement of all parties to the test.

7.1.2 *Flash X-ray (Photon Mode)*—The choice of facilities depends on the available dose rate as well as other factors including photon spectrum, pulse width and end-point energy. The selection of the pulse width is affected by; (*a*), the dose rate required, and (*b*), the ionizing dose accumulation per pulse. Finally, the FXR end-point energy for the photon made must be greater than 1 MeV to ensure device penetration.

7.1.3 *Flash X-ray (E-beam Mode)*—An FXR operated in the e-beam mode generally provides a higher dose rate than similar machines operated in the photon mode. However, testing in the e-beam mode requires that appropriate precautions be taken and special test fixtures be used to ensure meaningful results. The beam produces a large magnetic field, which may interfere with the instrumentation, and can induce large circulating currents in device leads and metals. The beam also produces air ionization, induced charge on open leads, and unwanted cable currents and voltages. E-beam testing is generally performed with the DUT mounted in a vacuum to reduce air ionization effects. Special dosimetry techniques are required to ensure proper measurement of the dose. Finally, the FXR endpoint energy must be greater than 2 MeV to ensure device penetration. some necessary precautions are:

7.1.3.1 The electron beam must be constrained to the region that is to be irradiated. Support circuits and components must be shielded.

7.1.3.2 The electron beam must be stopped within the test chamber and returned to the FXR to prevent unwanted currents in cables and secondary radiation in the exposure room.

7.1.3.3 All cables and wires must be protected from exposure to prevent extraneous currents. These currents may be caused by direct deposition of the beam in cables, or by magnetic coupling of the beams into the cable.

7.1.3.4 All cables and cable entries must be shielded from electromagnetic radiation caused by the firing of the FXR machine.

7.1.3.5 An evacuated chamber for the test is required to reduce the effects of air ionization.

7.2 *Dosimetry Equipment*—Dosimetry equipment shall include the following:

(*a*) a system for measuring ionizing dose, such as a thermoluminescent dosimeter (TLD) or calorimeter,

(*b*) a pulse shape monitor, and

(*c*) a dosimeter that allows the dose rate to be determined from electronic measurements, for example, a positive intrinsic negative (PIN) detector, Faraday cup, secondary emission monitor, or current transformer.

NOTE 1—PIN represents a semiconductor structure consisting of highly P and N regions on the two sides of an intrinsic or relatively pure region.

7.2.1 *Thermoluminescent Detector (TLD)*—Exposure of thermoluminescent detectors to ionizing radiation creates thermoluminescent centers that when subsequently heated, emit light. The radiant energy is proportional to the total absorbed dose in the detector. This type of detector can cover a dose range from approximately 0.1Mrd to 1Mrd (see Practice E 668).

7.2.2 *Calorimeter*—A silicon calorimeter system can be constructed by attaching a thermocouple to a small (1 by 1 by 0.1 mm) block of silicon. The thermocouple-silicon block assembly is surrounded by closed-cell polyurethane foam and mounted in an aluminum housing. The aluminum provides electron isolation and equilibration in a medium-energy photon environment, and the polyurethane foam provides thermal isolation. A typical thermal decay time constant for such a system is about 3 to 4 s and typical sensitivities are about 1000 to 1500 rd(Si)/μV.

7.2.3 *PIN Diodes*—A PIN diode is the solid state equivalent of an ionization chamber. The magnitude of photo-charge generated and collected in a back-biased diode is directly proportional to the absorbed dose. Since the generation rate for silicon is 4.3×10^9. . . rd(Si), 4.3×10^9 carrier pairs/rd (Si), these devices can be calibrated knowing only the detector geometry. Calibration depends on the PIN bias and may change with accumulated exposure. Most PIN diodes have a linear response up to a dose rate of approximately 1×10^{10} rd(Si)/s.

NOTE 2—**Caution:** Care must be taken when using PIN diodes to ensure that the indicated PIN dose rate is equivalent to that absorbed by the DUT. Factors that can affect dosimetry include the FXR photon spectrum, the method used to calibrate the PIN diode, and the location of the PIN diode relative to the DUT.

7.2.4 *Opti-chromic Dosimeters*—Opti-chromic dosimeters have many of the same advantages as TLDs. These devices are relatively small, passive, inexpensive, and retain accurate dose information for months between irradiation and measurement of dose. The useful dose range of these devices is 400rd(Si) to 20Krd(Si). The device response is nearly linear with dose. Opti-chromic dosimeters are calibrated in a Co^{60} cell using NIST traceable exposures. The dose response is independent of dose rate up to 10^{12}rd(Si)/s.

7.3 *Test Circuit*—The test circuit shall contain the device under test, wiring, and auxiliary components as required. It shall allow the application of power and bias signals at the device inputs and outputs. Power supply stiffening capacitors shall be included to keep the power supply voltage from changing more than 10 % of its specified value during and after the radiation pulse (see 8.4). Capacitors placed across the supply voltage shall be located as close to the DUT as possible, but shall not be exposed to the radiation beam. The test circuit shall allow the device under test to be tested under worst case conditions (see 6.4).

7.3.1 *Materials*—Test circuit materials and components shall not cause attenuation or scattering, which will perturb the uniformity of the beam at the test device position. The DUT shall be oriented so that its surface is perpendicular to the radiation beam.

7.4 *Cabling*—Cabling shall be provided to connect the test circuit board to the test instrumentation located in the instrumentation area. Coaxial cables, terminated in their characteristic impedance, shall be used for all input and output signals. Double shielded cables, triax, zipper tubing or other additional shielding may be required to reduce noise to acceptable levels.

7.5 *Transient Signal Measurement*—Oscilloscopes or transient digitizers shall be used to measure transient output voltages, the power supply current, and the dosimeter outputs.

7.6 *General Purpose Test Equipment*—Power supplies, voltmeters, pulse generators, and other basic test equipment that are required for testing are considered general purpose test equipment. This equipment shall be capable of meeting the test requirements and should be periodically calibrated in accordance with appropriate standards.

7.6.1 *Functional Testing*—Certain types of device burnout may not be detected unless a comprehensive electrical and functional test is performed prior to radiation exposure then repeated again after exposure. Such complete electrical and functional testing may not be possible while the DUT remains in the burnout test fixture, because of extensive cabling and test equipment requirements. Final determination of burnout damage is therefore determined by complete functional and comprehensive electrical testing after final exposure. However, a simplified functional check shall be performed on each DUT while in the burnout test fixture to ensure that the DUT is functional or has experienced a functional failure.

NOTE 3—In some cases, with the agreement of all parties involved with the test, parts with known bad bits (SRAMS) or equivalent defective elements in other part types can be used to initially determine the burnout failure level.

7.6.1.1 *Functional Testing Equipment*—Certain device types may be more susceptible to burnout when biased in static mode, whereas other part types may be more sensitive during certain portions of their normal switching waveforms. Metal-oxide semiconductor field-effect transistor (MOSFET) transistors, bipolar (NPN) and (PNP) transistors generally are tested using static conditions. Pulse width modulators may be most sensitive to burnout when the radiation pulse occurs on the turn-on point of the output switching transistor. Memory and microprocessor part types may need to be driven with a pattern to initialize the DUT to known conditions, and to verify functionality before and after radiation exposure. The equipment required for functional testing will therefore vary with the part type, the burnout circuit configuration selected as worst-case, and other factors. The DUT may also be upset as a result of the dose-rate pulse. Therefore, a minimum requirement is that after each radiation exposure a functional test shall be performed to verify that the pre-radiation conditions can be re-established, with power supply currents and output voltages at expected levels.

NOTE 4—**Caution:** Ionizing dose damage following an intense pulse of ionizing radiation may sometimes have a long recovery time. A functional test immediately following exposure may erroneously be interpreted as a burnout failure. Post-irradiation annealing must be considered when interpreting the results of functional testing.

8. Preparation of Apparatus

8.1 *Test Circuit Preparation*—The test circuit shall include as a minimum a test board, line drivers, electrical monitoring instruments, power supplies and cables to provide the required input biasing, input and output monitoring, and loading.

8.2 *Facility Preparation*—The radiation source shall be adjusted to operate in the specified mode and provide a radiation pulse width within the specified width range. The required dosimeters shall be installed as close as possible to the device under test. If special equipment is needed to control the temperature to the value specified in the test plan, this equipment shall be assembled and adjusted to meet this requirement.

8.3 *Test Circuit Noise Check*—A noise check shall be made prior to device burnout testing. This check shall be made with all circuitry connected, powered and monitored as when a device is tested. The noise check is performed by inserting a resistor circuit in place of the test device. Resistor values chosen shall approximate the active resistance of the device under test. A typical radiation pulse shall be applied while the specific output(s) are monitored. If any of the measured transient voltages are greater than 10 % of the expected test response, the test circuit is unacceptable and shall not be used without modification to reduce noise. The noise check is particularly critical when the FXR is operated in the e-beam mode due to the noise induced in the wiring.

8.4 *Power Supply*—Devices shall be biased at their maximum operating voltage. low impedance ($<1.0\Omega$) supply lines with stiffening capacitors (for example, 100-µf capacitor in parallel with a 0.01-µf high frequency capacitor) shall be used at the device supply lead to ground. The power supply current wave form shall be monitored as an indicator of peak photocurrent and latchup, burnout, and recovery.

9. Procedure

9.1 The procedures to be followed for high dose rate burnout testing are discussed here. This procedure shall include a test plan that has been approved by the qualifying agency or customer.

9.1.1 *Radiation Safety*—The health and safety requirements established by the local Radiation Safety Officer or Health Physicist shall be observed.

9.1.2 *Testing Requirement*—There are two possible test modes:

9.1.2.1 *Survival Test:* For a survival test, the part is exposed to a predetermined dose-rate level performed to determine the status of the device after being exposed. The test may or may not be a destructive test, depending upon factors such as dose rate, total dose, and maximum photocurrent observed during the test. If the part survives the test, the part is said to pass, that is, it meets the part specification.

9.1.2.2 *Failure Level Test:* For failure level tests, the actual dose-rate failure level of the device under test shall be determined. However, since tests near failure cannot be repeated on the same device, the failure level must be determined statistically by testing a number of devices.

9.2 *Test Plan*—The test plan must as a minimum include the following:

9.2.1 *Device Identification*—Device identification shall include manufacturer, date code, wafer lot number if available, and complete part number as well as other part numbers used in procuring the test samples. Test samples shall be serialized to permit applicable test data to be traceable to the individual device.

9.2.2 *Test Facility Selection*—The reasons for the facility choice along with current dose-rate level information verifying the ability to meet the test objectives shall be specified.

9.2.3 *Criteria for Ionization-Induced Burnout*—The measurement point(s) and signal characteristics that indicate a burnout has occurred shall be specified.

9.2.4 *Power Supply Requirements*—The bias voltage requirements and power distribution layout including stiffening capacitors shall be provided. In addition this layout shall be supported by analysis that verifies the adequacy of the test set-up.

9.2.5 *Loading Conditions*—Loading conditions are as follows:

9.2.5.1 *Device Output:* The logic levels, bias conditions, fan-out, supply voltage and impedance loading, etc., shall be provided.

9.2.5.2 *Device Input:* The input voltage conditions, source impedance, logic state, etc, shall be provided.

9.2.6 *Sample Size*—The sample that is sufficient to establish adequate confidence in the characterization of the burnout of the part and the rationale for the sample size and composition shall be provided in the test plan.

9.2.7 *Radiation Pulse Width(s)*—The selection of the pulse width shall be supported by analysis and specification in the test plan.

9.2.8 *Dosimetry Methods*—The dosimetry methods shall be described and documented. These methods shall conform to applicable ASTM standards.

9.2.9 *Test Sequence*—The testing sequence proposed to adjust the dose rate to determine the burnout threshold shall be provided.

9.2.10 *Radiation Levels (Step Size)*—For survival tests, the radiation test level shall be defined and agreed upon between the parties concerned prior to the test. For failure level testing, the dose-rate range should be estimated from the characteristics of the device material and construction in order to minimize the ionizing dose delivered to the DUT.

9.2.11 *Temperature*—The temperature of the devices during the test shall be specified.

9.2.12 *Ionizing Dose Limit*—The ionizing dose limit for the DUT shall be specified. This is the ionizing dose level where the device exceeds 50 % of its expected ionizing dose failure level.

9.3 *Test Procedures*—The following general procedures shall be followed for the test:

9.3.1 Set up the test equipment and calibrate the radiation source.

9.3.2 Perform a noise check and record the noise level on the instrumentation while using a dummy package.

9.3.3 Install the DUT in the test fixture, allow the DUT to reach test temperature, and verify functional performance.

9.3.4 To determine the failure threshold, begin at a factor of 10 below the predicted burnout point and increase the exposure level until maximum radiation level of the facility or a burnout is indicated. Perform a functionality test and record results and accumulated dose after each exposure.

9.3.5 For a pass/fail determination, expose the DUT at the specified level. The accumulated dose and functionality test results shall be recorded after each exposure.

9.3.6 Record measurement-point wave form(s) at each exposure level.

9.3.7 Record dosimetry.

10. Report

10.1 A test report shall be prepared that documents the devices tested by device type, manufacturer, date code, and lot/wafer identification if available. The report shall list by device serial number, pass/fail status of each device, and the doses or dose range delivered to each device in each radiation pulse. The test plan and procedure shall be either appended to the test report or referenced in the test report. As a minimum the report shall include the following information:

10.1.1 Device identification,

10.1.2 Test date and test operator,

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

10.1.4 Bias conditions, output loading, and test circuit,

10.1.5 Test set-up showing schematics, layout, shielding, etc.,

10.1.6 Test fixture description,

10.1.7 Description of dosimetry and its calibration,

10.1.8 Functional test conditions,

10.1.9 Criteria for failure,

10.1.10 Records of pass/fail level for each device tested,

10.1.11 Equipment list, calibration, etc.,

10.1.12 Results of noise tests,

10.1.13 Ambient temperature of test,

10.1.14 Tabulation of the results of the test, and

10.1.15 Device states concerning know defects if applicable.

11. Keywords

11.1 burnout; failure; high dose-rate; integrated circuits; ionizing radiation; latchup; microcircuits; semiconductor devices; survivability