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Designation: F980 − 16

Standard Guide for Measurement of Rapid Annealing of Neutron-Induced Displacement Damage in Silicon Semiconductor Devices[1]

This standard is issued under the fixed designation F980; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide defines the requirements and procedures for testing silicon discrete semiconductor devices and integrated circuits for rapid-annealing effects from displacement damage resulting from neutron radiation. This test will produce degradation of the electrical properties of the irradiated devices and should be considered a destructive test. Rapid annealing of displacement damage is usually associated with bipolar technologies.

1.1.1 Heavy ion beams can also be used to characterize displacement damage annealing (**1**)[2], but ion beams have significant complications in the interpretation of the resulting device behavior due to the associated ionizing dose. The use of pulsed ion beams as a source of displacement damage is not within the scope of this standard.

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

1.3 *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 consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel
E265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32
E666 Practice for Calculating Absorbed Dose From Gamma or X Radiation
E720 Guide for Selection and Use of Neutron Sensors for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics
E721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics
E722 Practice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics
E1854 Practice for Ensuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts
E1855 Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors
E1894 Guide for Selecting Dosimetry Systems for Application in Pulsed X-Ray Sources

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *B*—gain also known as the common emitter gain. The ratio of the collector current over the base current at a constant V_{CE}.

3.1.2 *annealing function*—the ratio of the change in the displacement damage metric (as manifested in device parametric measurements) as a function of time following a pulse of neutrons to the change in the residual late-time displacement damage metric remaining at the time the imparted damage achieves quasi-equilibrium.

3.1.2.1 *Discussion*—This late-time quasi-equilibrium time is sometimes set to a fixed time on the order of approximately 1000 s, or it is, as in Test Method E1855, set to a displacement damage measurement made after temperature/time stabilizing thermal anneal procedure of 80°C for 2 h. Fig. 1 shows an example of the annealing function for a 2N2907 pnp bipolar transistor with an operational current of 2 mA during and after the irradiation. The displacement damage metric of interest is often the reciprocal gain change in a bipolar device. This damage metric is widely used since the Messenger-Spratt equation (**2, 3**) states that this quantity, at late time, is

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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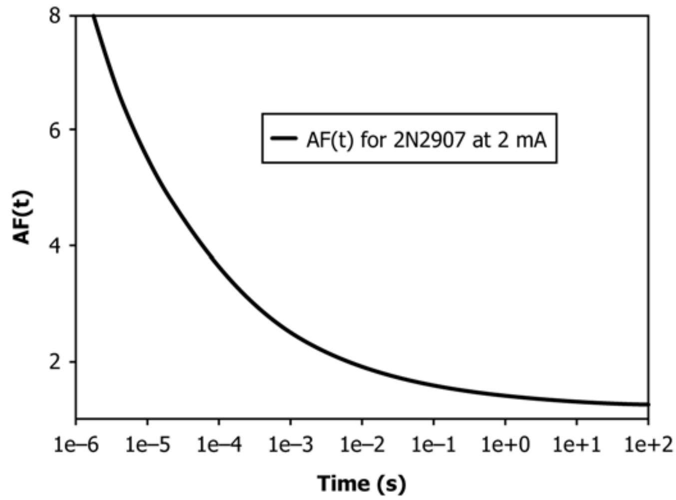


FIG. 1 Example Gain Annealing Function for a 2N2907 Bipolar Transistor

proportional to the 1-MeV(Si) equivalent fluence, see Practice E722. In this case the

$$\left(\frac{1}{G_\infty} - \frac{1}{G_0}\right) = k\Phi \quad (1)$$

Φ is the 1-MeV(Si)-equivalent fluence, k is a device-specific displacement damage constant referred to as the Messenger constant, G_0 is the initial gain of the device, and G_∞ is the late-time quasi-equilibrium gain of the device. For this damage metric, the anneal function, *AF(t)*, is given by:

$$AF(t) = \frac{\frac{1}{G(t)} - \frac{1}{G_0}}{\frac{1}{G_\infty} - \frac{1}{G_0}} \quad (2)$$

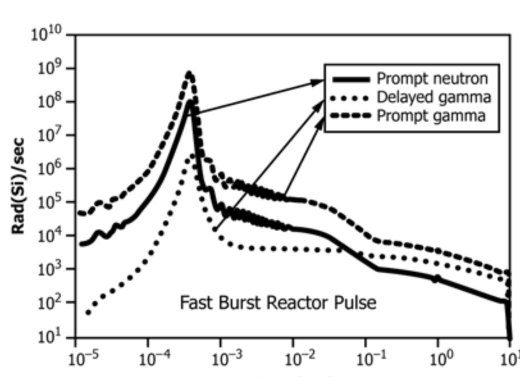
where *G(t)* is the gain of the device at a time *t*.

3.1.2.2 *Discussion*—The annealing function has typical values of 2 to 10 for time periods extending out to several thousands of seconds following irradiation; see Refs **(4-10)**. The annealing function decreases to unity at late time, "late time" is taken to be the time point where the G_∞ late time quasi-equilibrium device gain was determined.

3.1.3 *displacement damage effects*—effects induced by the non-ionizing portion of the deposited energy during an irradiation. The dominant effect of displacement damage in bipolar silicon devices is a reduction in the minority carrier lifetime and a reduction in the common-emitter current gain.

3.1.4 *in situ tests*—electrical measurements made on devices before, after, or during irradiation while they remain in the immediate vicinity of the irradiation location. All rapid-annealing measurements are performed in situ because measurement must begin immediately following irradiation (usually <1 ms).

3.1.4.1 *Discussion*—For reactor neutron irradiations there will be a gamma environment as well as a neutron pulse. In addition to the neutron displacement damage, the transient photocurrent from the gamma environment may affect the electrical measurements. During a fast burst reactor pulse the peak gamma dose rate can exceed 1.E8 rad(Si)/s. The induced photocurrents may interfere with the determination of the early-time (< 100 ms) device gain. Fig. 2 shows a representa-



NOTE 1—Fig. 2 shows the radiation components from a maximum pulse [$\Delta\Theta$ = 300°C, neutron fluence = 3.4×10^{14} 1–MeV(Si)/cm^2] in a fast burst reactor. The wiggles in the millisecond time period are a real effect and represent the temperature-induced shock oscillations in the reactor power as a result of the fuel expansion. The time-dependence of the reactor pulse was measured with a diamond PCD and the calculations were performed to deconvolute the radiation components of the reactor pulse **(11,12)**.

FIG. 2 Representative Time-dependent Ionizing Dose from a Fast Burst Reactor

tive time profile for the prompt gamma, prompt neutron, and delayed gamma radiation components for a maximum pulse in a fast burst reactor. After a reactor pulse the delayed fission gamma environment will produce a photocurrent environment that extends out to the time when the device is removed from the reactor. The time-dependent importance of the device photocurrent response will vary with the operational currents within the device itself. At low operational currents the photocurrent interference current will exceed the operational currents for a longer period of time.

3.1.5 *LET—*linear energy transfer, also called the linear electronic stopping power, is the energy loss of an ionizing particle due to electronic collisions per unit distance into a material.

3.1.6 *remote tests—*electrical measurements made on devices that are physically removed from the irradiation location. For the purpose of this guide, remote tests are used only for the characterization of the parts before and after they are subjected to the neutron radiation (see 6.4).

4. Summary of Guide

4.1 A rapid-annealing radiation test requires that continual or periodic time-sequential electrical-parameter measurements of key parameters of a device be made immediately following exposure to a short pulse of neutron radiation capable of causing significant displacement damage.

4.2 Because many factors enter into the effects of the radiation on the part, parties to the test must establish many circumstances of the test before the validity of the test can be established or the results of one group of parts can be meaningfully compared with those of another group. Those factors that must be established are as follows:

4.2.1 *Radiation Source—*The type and characteristics of the neutron radiation source to be used (see 6.2).

4.2.2 *Dose Rate Range—*The range of ionizing dose rates within which the neutron exposures must take place. These dose rates and the subsequent device response must be taken into account in the interpretation of the parametric measurements being made (see 6.6).

4.2.3 *Operating Conditions—*The test circuit, electrical biases to be applied, and operating sequence (if applicable) for the part during and following exposure (see 6.5).

4.2.4 *Electrical Parameter Measurements—*The pre-irradiation measurements to be made before the test and post-irradiation measurements to be made after the radiation exposure on the test unit. These measurements include the measurement of relevant electrical properties accompanying changes in annealing-sensitive parameters of interest in the test.

4.2.5 *Time Sequence—*The exposure time, time after exposure when measurements of the selected parameter(s) are to begin, time when measurements are to end, and the time intervals between measurements.

4.2.6 *Neutron Fluence Levels—*The fluence range required to attain the desired damage to the device.

4.2.6.1 *Total Ionizing Dose Levels—*If the part is sensitive to an accompanying type of radiation (such as gamma rays) the levels to which the part is exposed before the rapid annealing measurement is affected (see 6.4).

*Discussion—*The damage from total dose can depend upon the dose rate and the LET of the irradiating particle **(13)**. For reactor irradiations, ionizing dose can result from the neutrons or the associated gamma-rays. In the case of neutrons, the ionizing dose is delivered by the residual ions resulting from nuclear reactions. The relevant reactions can be elastic, inelastic, spallation, or transmutation reactions.

4.2.7 *Dosimetry—*The type of monitor and the read-out technique used to measure the radiation levels. The selection of a dosimetry system is dependent to some extent on the radiation source selection.

4.2.7.1 Since a short pulsed radiation source is implied for a rapid-annealing measurement, a time profile of the radiation intensity and its time relationship to the subsequent measurements should be obtained (see 7.1).

4.2.8 *Temperature—*The temperature during exposure and the allowable temperature change during the time interval of the rapid-annealing measurement (see 6.7).

4.2.9 *Experimental Configuration—*The physical arrangement of the radiation source, test unit, radiation shielding, and any other mechanical or electrical elements of this test.

5. Significance and Use

5.1 Electronic circuits used in many space, military, and nuclear power systems may be exposed to various levels and time profiles of neutron radiation. It is essential for the design and fabrication of such circuits that test methods be available that can determine the vulnerability or hardness (measure of survivability) of components to be used in them. A determination of hardness is often necessary for the short term (≈100 µs) as well as long term (permanent damage) following exposure. See Practice E722.

6. Interferences

6.1 There are many factors that can affect the results of rapid-annealing tests. Care must be taken to control these factors to obtain consistent and reproducible results.

6.2 *Pulsed Neutron-Radiation Source—* Because the objective of a rapid-annealing test is to observe short-term damage effects, it is implied that this damage is incurred in a short time period and is severe enough to be easily measured. These factors imply a pulsed neutron source. The most commonly used source for rapid-annealing tests is a pulsed reactor. There are two types commonly used; the bare-assembly fast-burst reactor and the water-moderated TRIGA type (see Ref **(14)**). A less common, but useful neutron source is a spallation neutron source **(15)**.

6.3 *Energy Spectrum—*The neutron energies should be known to ensure correlation with design requirements. It should also be known that adequate damage to the part can be inflicted. Neutron fluences (n/cm^2) are commonly specified in terms of 1-MeV silicon damage equivalent fluence or as the total neutron fluence above a given energy (see 7.5.1 and Guides E720 and E721, and Practice E722).

6.4 *Effects of Other Radiation—*Some parts that will be evaluated for neutron-induced rapid-annealing effects may also be affected by other types of radiation that may accompany the particles (such as gamma radiation accompanying the generation of the neutrons). (See Practice E666.) For this reason, characterization of the part type to both ionizing and displacement types of radiation is necessary prior to the rapid-annealing tests.

6.5 *Bias*—Rapid annealing effects from displacement-damage are usually associated with bipolar devices. Most of these effects are related to the electron density in semiconductor device junctions, which is a function of the operating-current bias level. Operating conditions during exposure and the rapid-annealing periods may be chosen to give a large or small degree of annealing as desired. Lacking any customer preference for the bias condition, those conditions that approximate the intended device application should be used.

6.6 *Dose Rate:*

6.6.1 The excess charge carrier concentration depends on the dose rate. High densities of excess carriers can affect trapping site charge states as well as carrier mobilities and lifetimes, altering post-radiation trapped charge densities and distributions. Since the neutron radiation is accompanied by ionizing radiation, the rapid-annealing measurements may be affected. The charge carriers created by ionizing radiation act just like those carriers injected by biasing the device (see 6.5).

6.6.2 Because the device parameter measured during a rapid-annealing test may be significantly altered by a high dose rate, it is necessary to ensure (through some functionality check) that the dose rate during irradiation does not reach a level that will upset the parameter being measured.

6.6.3 Photocurrents produced by the excess carriers generated by an ionizing radiation can alter internal bias levels of a semiconductor device, thereby causing a variation in the rapid-annealing response. Care must be taken to ensure that dose-rate levels remain below a level that will cause debiasing of the device.

6.6.4 For all of these reasons, the dose-rate range permitted furing the rapid-annealing measurements must be considered by the parties to the test.

6.7 *Temperature:*

6.7.1 Because annealing of neutron-induced displacement damage is also dependent upon thermally activated processes as well as current injection, the temperature during irradiation and testing can affect the rapid-annealing measurements. It is recommended that all radiation exposures and measurements be done at 24 ± 6°C unless unique requirements or unusual environmental conditions dictate otherwise.

6.7.2 Because rapid annealing is affected by temperature, it is important to monitor possible temperature rise resulting from the pulse of radiation or a temperature rise of the radiation source.

6.7.3 Device heating may also occur from high device current. Injection level of device operation is important and should be known at all times; see Refs (**4-10**,**14**, **16**).

6.7.4 Consideration should be given for temperature changes that the devices may experience after radiation and prior to quasi-equilibrium measurement.

6.8 *Handling*—As in any other type of testing, care must be taken in handling the parts. This especially applies to parts that are susceptible to damage from electrostatic discharge.

6.9 *Radiation Damage*—If a test fixture is used over a long period of time in a radiation environment, components and materials of the fixture can become damaged, resulting in incorrect parameter readings during the test. Such fixtures should be checked regularly for socket or printed-circuit-board leakage and degradation of any peripheral components used in the test.

6.10 *Induced Radioactivity*—Because low-energy (thermal) neutrons often accompany the high-energy neutrons required to cause displacement damage, it is necessary to realize that both fast and thermal neutrons cause the parts to become radioactive. Prescribed radiation-safety practices must be exercised in handling these parts.

6.11 *Parameter Selection:*

6.11.1 Selection of the electrical parameter to be monitored as the indicator of the rapid-annealing characteristics can be critical to the test and may be very difficult. The most desirable condition is one that enables the experimenter to monitor a parameter whose degradation is proportional to the neutron fluence and is also a good indicator of the functional behavior of the device. If these criteria cannot be met, then a parameter should be selected that is easily measured and is prominent in the planned use of the part.

6.11.2 The parameter selected for the rapid-annealing measurement must be fully characterized for the part type as a function of fluence prior to the test. This knowledge enables the proper selection of the fluence level to be used in the test.

6.11.3 Interpretation of the results can be very difficult unless the relationship of the electrical parameters to the fluence is well known. This difficulty applies to any part with a nonlinear parametric relationship to fluence.

6.12 Because the pulse of neutrons will vary in duration from source-to-source, it should be noted that annealing is occurring concurrently with the introduction of the damage.

7. Apparatus

7.1 *Pulsed Neutron Source,* with adequate neutron energy and fluence to cause significant displacement damage must be used. It is extremely helpful if the source is readily accessible and dosimetry techniques for determining the fluence and radiation time profile are already established. If not, dosimetry measurements in accordance with referenced guidelines will be necessary (Guides E720, E721 and Practice E1854).

7.1.1 *Fast-Burst Reactor*—These neutron sources possess many features that are desirable for rapid-annealing measurements. They can produce a high neutron fluence in a short burst (approximately 100 µs) with an accompanying gamma-radiation dose of less than 1×10^3 Gy(Si) and a dose rate of, $\leq 1 \times 10^7$ Gy(Si)/s. Selective shielding can be used to alter the neutron-to-gamma ratio if it is necessary. The neutron-to-gamma ratio of fast-burst reactors is less than 4.5×10^{11} [(n/cm^2)/Gy(Si)].

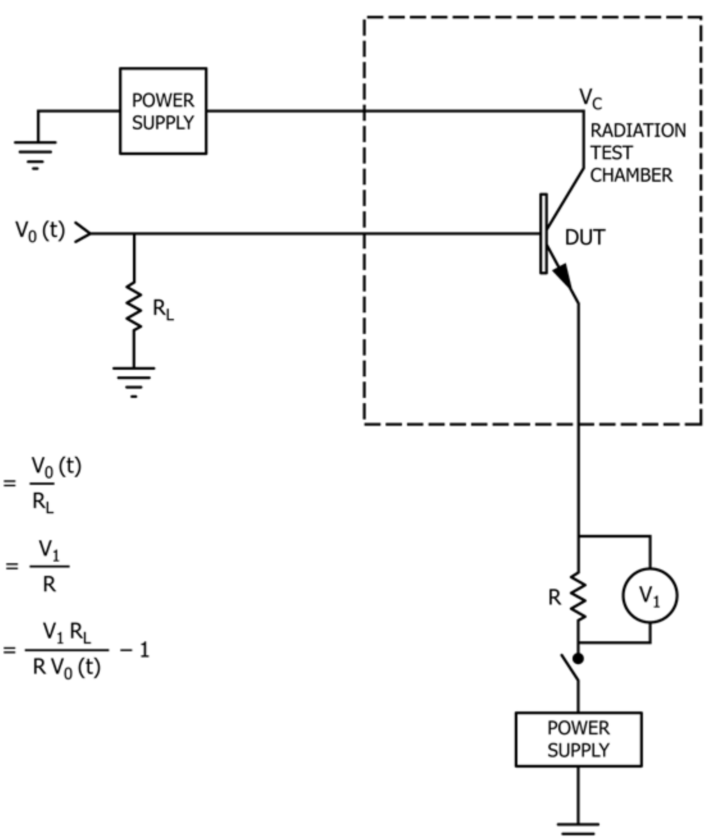
7.1.2 *Water-Moderated Pulsed Reactor*— These neutron sources typically have a pulse width greater than 7 ms and, therefore, will not allow measurement of rapid annealing as quickly as a fast-burst reactor. In addition, this type of reactor can have a relatively high number of low-energy neutrons and will thereby cause the device under test to become more radioactive. The neutron-to-gamma ratio of the central cavity in a water-moderated pulsed reactor is approximately 4×10^{10} (n/cm^2) / (Gy(Si)).

7.1.3 *Spallation Neutron Sources*—When a high-energy proton beam is incident on a high atomic number target, spallation neutrons are generated. Available proton storage rings can provide high flux proton pulses in time intervals as short as 160 ns. Due to available proton beam currents, the neutron fluence in a pulse is typically about $<1 \times 10^{12}$ n/cm^2. Interest in the use of spallation neutron sources has arisen due to the closure of most fast burst reactors in an attempt to limit access to sources of highly enriched uranium. The neutron-to-gamma ratio in a spallation neutron source is similar to that in a fast burst reactor source. Since high energy, (> 250 MeV), protons have a long range in the target, the test devices must be located outside the path of the incident proton beams in order to avoid interference from proton-induced damage effects. The useful irradiation area in a spallation source is limited by the low fluence in a pulse and the fluence gradient away from the point where the protons impact the target. The useful irradiation area is typically < 2 cm^2.

7.2 *Bias Circuit*—The bias circuit may be simple or complex, depending on the part type and parameter to be monitored. It may be made to accept a single device or several devices, depending on requirements. Design and fabrication practices that prevent oscillations, minimize leakage currents, prevent device damage, and promote accurate measurements should be used. For in situ measurements, provisions must be made to minimize cable noise and other forms of noise that may be induced into the circuit by the radiation source or any of its ancillary equipment.

7.3 *Test Instrumentation*—Standard device parameter measurement instruments are required. Depending on the device type and parameter to be measured, these can range from simple breadboard circuits to complex, computer-controlled IC test systems. All equipment is to be in calibration for the entire period of the test.

7.4 *Typical Test Setup*—A typical test setup for characterizing the rapid-annealing response of a bipolar device using a fast-burst reactor as the source of neutrons is shown in Fig. 3.



$$I_B(t) = \frac{V_0(t)}{R_L}$$

$$I_E = \frac{V_1}{R}$$

$$\beta(t) = \frac{V_1 R_L}{R V_0(t)} - 1$$

NOTE 1—For a constant current, *R* must be large (or use a constant-current source).

NOTE 2—Switch must be a mercury-wetted type or a comparable nonbounce switch.

NOTE 3—$V_1 >> V_0(t)$.

NOTE 4—For an IC, the test circuit and parameter to be measured may be significantly different from those shown.

NOTE 5—A current limiting diode is often used by the power supply leg to prevent photocurrent induced saturation of diagnostic equipment (**15**).

FIG. 3 Typical Schematic of a Simple Bipolar Rapid-Annealing Test Circuit

7.5 *Dosimetry System:*

7.5.1 The neutron fluence for each exposure is measured with activation foils. Often a single activation sensor such as sulfur or nickel (see Test Methods E264 and E265) can be used, once the spectrum has been determined, in accordance with referenced guidelines.

7.5.2 Gamma dosimetry for the fast-burst reactor is performed using CaF_2:Mn. Thermoluminescent Dosimeters (TLDs) or a silicon calorimeter to determine dose and PIN photo diodes or photoconducting devices (PCDs) to establish the dose rate; see Guide E1894. Preselected fluence levels and dose rates are then obtained by irradiating at a selected reactor output. (Proper use of TLD systems is described in Practices E666.)

7.5.2.1 *Discussion*—LiF TLDs should not be used in reactor environments due to their sensitivity response to thermal-neutron-induced ionization. CaF_2: Mn TLDs show very limited response to ionizing dose delivered by neutrons due to their LET-dependent response (**17**).

7.5.3 Other dosimetry can be used for the determination of both neutron radiation and gamma radiation levels. The calibration of dosimetry systems should be traceable to NIST standards.

8. Procedure

8.1 Parties to the test must first establish the circumstances of the test. As a minimum, they should establish the items specified in 4.2 and consider all of the possible interferences described in Section 6 when making these decisions.

8.2 Prepare bias fixtures, test circuits, and test programs.

8.3 Do preliminary source dosimetry, as needed, and establish the dosimetry system calibration.

8.4 Make pre-irradiation parameter or functional measurements, or both.

8.5 Bias the parts as agreed upon between the parties to the test. Irradiate to the agreed radiation level.

8.6 Make measurements at the agreed times following the radiation exposure.

8.7 If the preselected damage level of the device allows additional exposures, repeat 8.5 and 8.6, if desired.

9. Report

9.1 As a minimum, report the following information:

9.1.1 Information identifying the devices tested. All information available for device identification should be included; for example, device type, serial number, manufacturer, date lot code, diffusion lot designation, wafer lot designation, and so forth. The history of the devices being tested should be recorded. This is often captured using a "traveler" or similar document that is associated with the device and records the history of the environment seen by the device since it was purchased.

9.1.2 A listing of items agreed upon between the parties to the test including all the conditions described in 4.2.

9.1.3 A record of the irradiation date/time and facility operation number. This should include a reference back to neutron and gamma radiation field characterization data rrepresentative of the exposure conditions. See Sections 5.4 and 5.7 of Practice E1854.

9.1.4 Dosimetry records, including quantified measurement uncertainties, from the irradiation that supports a full characterization of the radiation environment seen by the devices. This typically involves use of both a neutron and a gamma monitor, see Section 5.8 of E1854.

9.1.5 A schematic of the bias circuit.

9.1.6 A diagram of the physical test configuration.

9.1.7 A tabulation of test parameter measurement data including measurements sufficient to determine the accuracy and precision of the data system. Reference data pointing back to the instrument calibration records should also be recorded.

9.1.8 Bias levels numerically defined.

9.1.9 Temperature information at the time of irradiation.

9.1.10 Ionizing dose information.

9.1.11 Quasi-equilibrium defined.

10. Keywords

10.1 annealing factor; annealing function; displacement damage; integrated circuits; neutron damage; neutron degradation; photoconducting device; rapid annealing; semiconductor devices

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