~~Designation:F980M–96 (Reapproved 2003)~~ Designation: F980 – 10

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

This standard is issued under the fixed designation ~~F980M;~~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.

~~1.2~~

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

F1032 Guide for Measuring Time-Dependent Total-Dose Effects in Semiconductor Devices Exposed to Pulsed Ionizing Radiation (Discontinued 1994)

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

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[1] This guide is under the jurisdiction of ASTM Committee F01 on Electronics and is the direct responsibility of Subcommittee F01.11 ~~.~~

~~Current edition approved June 10, 2003. Published June 2003. Originally approved in 1986. Last previous edition approved in 1996 as F980M–96. DOI: 10.1520/F0980M-96R03.~~on Nuclear and Space Radiation Effects.

Current edition approved Dec. 1, 2010. Published January 2011. Originally approved in 1986. Last previous edition approved in 2003 as F980M – 96(2003). DOI: 10.1520/F0980-10.

~~[2] 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.~~

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

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3.1.1 *annealing ~~factor~~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 and the change in the residual late-time displacement damage metric remaining at the time the initial damage achieves quasi ~~equilibrium, approximately 1000 s.~~ equilibrium.

3.1.1.1 *Discussion*~~—Annealing factors have typical values of 2 to 10 for these periods of time following irradiation; see Refs~~ **—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 low temperature thermal stabilizing 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 proportional to the 1-MeV(Si) equivalent fluence, see Practice E722. In this case the**

(1) $(1G\infty - 1G0) = k\Phi$

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:

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

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

3.1.1.2 *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 **(~~1~~4, ~~2~~5, ~~3~~6, ~~4~~7, ~~5~~8, ~~6~~9, ~~7~~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.

3.1.2 *displacement damage effects*—effects induced by the non-ionizing portion of the deposited energy during an irradiation. The non-ionizing energy results in lattice displacements and the generation of phonons in a lattice. Displacement damage effects are commonly induced by neutrons or heavy ion irradiation. There is a displacement component to high energy electron and photon irradiations. 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.

3.1.3 *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).

~~3.1.3~~

3.1.3.1 *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 representative 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

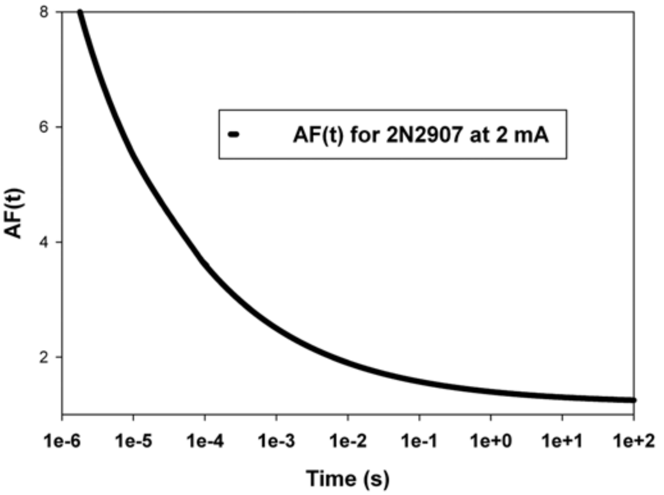
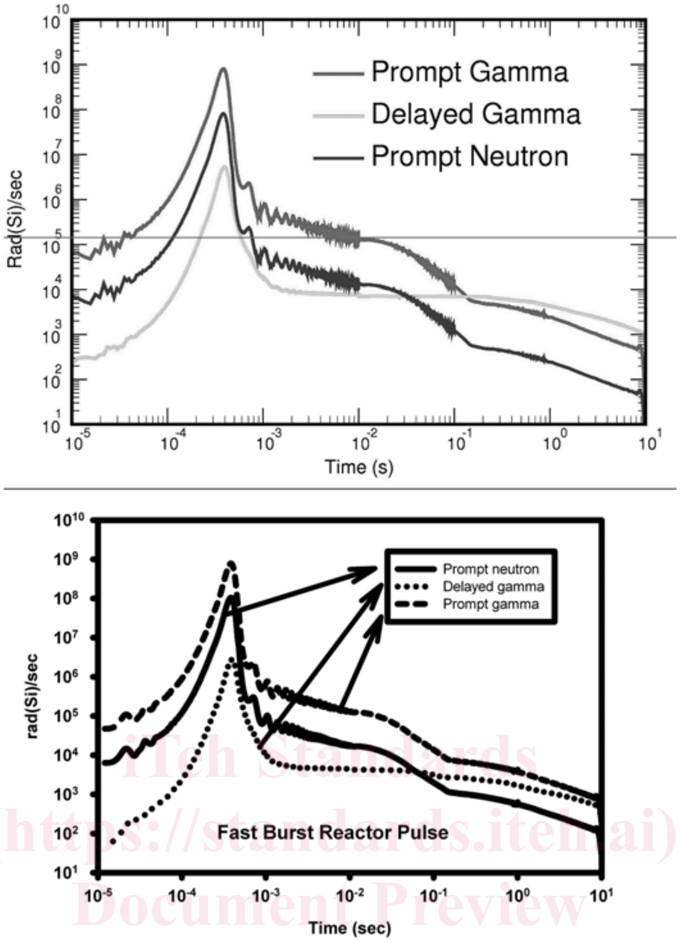


FIG. 1 Example Annealing Function for a 2N2907 Bipolar Transistor



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

operational currents for a longer period of time.

3.1.4 *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.

3.1.5 *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 ~~should not influence~~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 and postirradiation measurements to be made beginning after the radiation expense on the test unit and the measurements of accompanying changes in the annealing-sensitive parameters to be made beginning immediately after exposure.

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 sustain 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 can be 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 and technique used to measure the radiation levels. This 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 ~~is extremely helpful~~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 nonvulnerability) 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 **(~~8~~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 equivalence ~~or in~~as a percentage of 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 with neutrons). (See Guide F1032 and 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 ~~must~~may be chosen to give a large or small degree of annealing as desired. Lacking any customer preference ~~on~~for the ~~most desirable bias,~~ bias condition, those conditions that approximate the ~~actual~~intended device application ~~may~~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. ~~If~~Since the neutron radiation is accompanied by~~ an~~ 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.