



Designation: E1855 – 10

Standard Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors¹

This standard is issued under the fixed designation E1855; 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 test method covers the use of 2N2222A silicon bipolar transistors as dosimetry sensors in the determination of neutron energy spectra, and as silicon 1-MeV(Si) equivalent displacement damage fluence monitors.

1.2 The neutron displacement damage is especially valuable as a neutron spectrum sensor in the range 0.1 to 2.0 MeV when fission foils are not available. It has been applied in the fluence range between 2×10^{12} n/cm² and 1×10^{14} n/cm² and should be useful up to 10^{15} n/cm². This test method details the steps for the acquisition and use of silicon 1-MeV equivalent fluence information (in a manner similar to the use of activation foil data) for the determination of neutron spectra.

1.3 In addition, this sensor can provide important confirmation of neutron spectra determined with other sensors, and yields a direct measurement of the silicon 1-MeV fluence by the transfer technique.

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

1.5 *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 requirements prior to use.*

2. Referenced Documents

2.1 The ASTM standards E170, E261, and E265 provide a background for understanding how sensors are used in radiation measurements and general dosimetry. The rest of the standards referenced in the list discuss the choice of sensors, spectrum determinations with sensor data, and the prediction of neutron displacement damage in some semiconductor devices, particularly silicon.

¹ This test method is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.07 on Radiation Dosimetry for Radiation Effects on Materials and Devices.

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2.2 ASTM Standards:²

- E170 Terminology Relating to Radiation Measurements and Dosimetry
- E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
- E265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32
- 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
- E844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)
- E944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA)
- E1854 Practice for Ensuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts
- E2005 Guide for Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron Fields
- E2450 Practice for Application of CaF₂(Mn) Thermoluminescence Dosimeters in Mixed Neutron-Photon Environments

3. Terminology

3.1 Symbols:

Φ_1 = the silicon 1-MeV equivalent fluence (see Practice E722).
 $h_{FE} = i_c/i_b$ where i_c is the collector current and i_b is the base current, in a common emitter circuit.

4. Summary of Test Method

4.1 Gain degradation of 2N2222A silicon bipolar transistors measured in a test (simulation) environment is compared with that measured in a reference neutron environment. The Φ_{1r} in

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.

the reference environment is derived from the known reference spectrum and is used to determine a measured Φ_{1r} in the test environment (1,2)³ by the transfer technique. The subscripts r and t refer to the reference and test environments respectively.

4.2 The measured Φ_{1r} may be used as a sensor response in a spectrum adjustment code in a manner similar to the use of reaction foil activities to determine the spectrum (3,4).

4.3 Spectra compatible with the responses of many sensors may be used to calculate a more reliable measure of the displacement damage.

5. Significance and Use

5.1 The neutron spectrum in a test (simulation) environment must be known in order to use a measured device response in the test environment to predict the device performance in an operational environment (see Practice E1854). Typically, neutron spectra are determined by use of a set of sensors that have response functions that are sensitive over the neutron energy region to which the device under test (DUT) responds (see Guide E721). In particular, for silicon bipolar devices exposed in reactor neutron spectra, this effective energy range is between 0.01 and 10 MeV. A typical set of activation reactions that lack fission reactions from nuclides such as ²³⁵U, ²³⁷Np, or ²³⁹Pu, will have very poor sensitivity to the spectrum between 0.01 and 2 MeV. For a pool-type reactor spectrum, 70 % of the DUT electronic damage response may lie in this range. Often, fission foils are not included in the sensor set for spectrum determinations because their use must be licensed, and they require special handling for health physics considerations. The silicon transistors provide the needed response to define the spectrum in this critical range.

5.2 If fission foils are a part of the sensor set, the silicon sensor provides confirmation of the spectrum shape.

5.3 Bipolar transistors, such as type 2N2222A, are inexpensive, are smaller than fission foils contained in a boron ball, and are sensitive to a part of the neutron spectrum important to the damage of modern silicon electronics. They also can be used directly in arrays to map 1-MeV(Si) equivalent fluence. The proper set of steps to take in reading the transistor-gain degradation is the primary subject of this test method.

5.4 Fig. 1 shows the energy-dependence of the displacement damage function for silicon. As can be seen from the figure, the major portion of the response for the silicon transistors will generally be above 100 keV. The currently recommended silicon damage function is listed in Practice E722.

6. Apparatus

6.1 A transistor with demonstrated response in agreement with calculated Φ_1 values in widely varied environments is the silicon bipolar transistor 2N2222A. It is recommended that three or more of these transistors be calibrated together and used at each location to be characterized. At least three others should be used as temperature correction devices (control devices) during readout. The control transistors should be exposed one time to a calibration exposure of about 1.0×10^{13} n/cm² 1-MeV(Si) equivalent fluence and then annealed (baked out) at 180°C for 24 h followed by ambient air cooling before being used as controls. These control transistors are not exposed again to radiation during the testing steps, but are read with the exposed transistors to provide temperature correction.

6.2 A dry oven for annealing is needed to stabilize the gain after both the calibration-exposure and gain readout are completed for the reference environment. The oven shall be able to maintain the set temperature to within $\pm 3.0^\circ\text{C}$ at 80°C and at 180°C. It would be prudent to have a timer for automatic shutdown and an emergency power system (UPS). Shutdown with a timer will require a door-opening mechanism for ambient air-cooling.

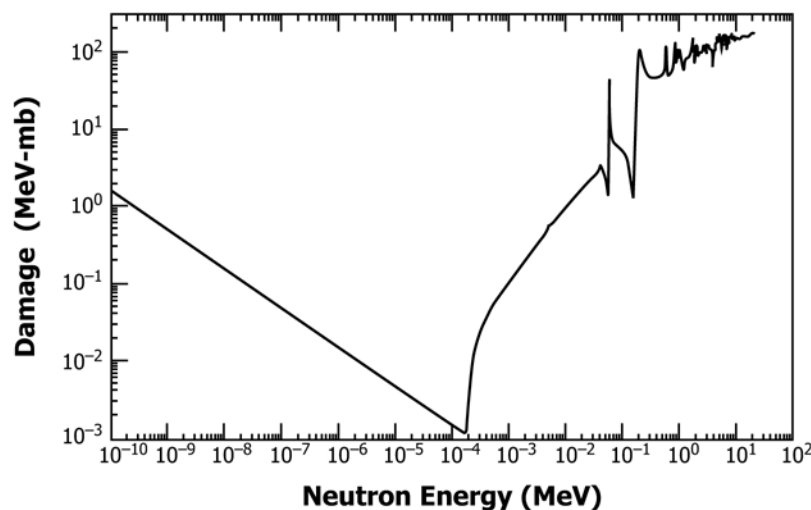


FIG. 1 Silicon Displacement Damage Response Function

³ The boldface numbers in parentheses refer to a list of references at the end of this test method.

6.3 An electronic system is required to maintain appropriate transistor bias and currents and to read the currents for the gain measurements. It is recommended that a programmable semiconductor parameter tester (such as a Hewlett Packard 4145A) be used. A programmable tester can operate in pulsed mode to control heating effects and provide gain values quickly. The parameter tester determines the common emitter current gain by injecting a pulse of current into the base region, measuring the collector current, and determining the current ratio i_c/i_b at a fixed bias of 10 V. The bias voltage is measured between the collector and the base (see Ref (5)).

6.4 A reference neutron source (see Guide E2005) for calibration of the transistors is required. The neutron fluence and neutron fluence spectrum of the reference source must be known. National Institute for Standards and Technology (NIST) benchmark fields (6) are recommended for use as primary standards, and a well characterized Fast Burst Reactor (FBR), such as the one at White Sands Missile Range, is recommended as a reference benchmark field.

6.5 A suitable monitor such as a nickel foil should be exposed along with the transistors during calibration to relate to the magnitude of the neutron fluence. A photon-sensitive detector such as a CaF_2 thermoluminescent detector (TLD) shall be included in each test package to monitor the gamma-ray dose so that a correction can be made for the transistor damage from gamma-rays. Care must be taken in the determination of the gamma environment to correct for any neutron response from the photon-sensitive detector that is used. Practice E2450 provides guidance on how to correct a $\text{CaF}_2\text{:Mn}$ TLD for the neutron response.

NOTE 1—Ionizing dose is produced by photon irradiation in the bulk silicon and SiO_2 . The ionizing dose can induce trapped holes and interface states in the oxide of the silicon devices. This resulting trapped charge can induce electric fields that change the gain in a bipolar device.

7. Description of the Test Method

7.1 2N2222A transistors exhibit a range of initial gain values and responses, but each responds linearly with 1-MeV(Si) equivalent fluence, Φ_1 , at fixed collector current according to the Messenger-Spratt equation (7), if gamma rays do not contribute to the change of gain.

$$\frac{1}{h_{FE\Phi}} - \frac{1}{h_{FEO}} = K_\tau \Phi(1 \text{ MeV}) \quad (1)$$

The term h_{FEO} is the common emitter current gain at some fixed collector current before irradiation in the test environment, and $h_{FE\Phi}$ is the same quantity measured at the same collector current after irradiation. K_τ is the damage constant. If gamma-ray dose contributes to the change in the reciprocal of the gain, then that contribution must be subtracted from the left side of Eq 1 (see 8.3).

7.2 A semiconductor parameter analyzer may be used to determine h_{FE} . A basic schematic circuit used by semiconductor analyzers for measuring $h_{FE} = i_c/i_b$ is shown in Fig. 2. Any equivalent method for making the electrical measurement is acceptable but the experimenter must ensure that the currents do not exceed the limits detailed in 8.1.2 and 8.1.3.

7.3 Since K_τ differs for each transistor, each must be calibrated. When the technology of manufacture is such that

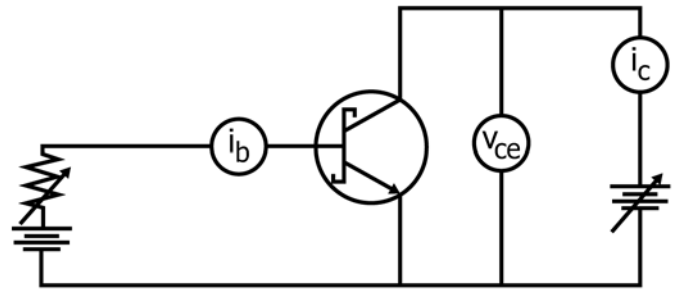


FIG. 2 Schematic for Transistor Read-Out

the K_τ 's within a batch are the same to within a few percentage points, a calibration by batch may be satisfactory. A typical value for K_τ is about $1.5 \times 10^{-15} \text{ cm}^2/\text{neutron}$ for a collector current of 1 mA.

7.4 The linearity of response of a given batch of transistors shall be verified by exposure of samples of the batch to at least three levels of neutron fluence covering the range in which the devices will be used.

7.5 The calibration is accomplished by exposing the transistors in a reference field for which the absolute values of the neutron fluence spectrum are known over the neutron energy range in which significant damage is caused. The 1-MeV(Si) equivalent fluence of the reference environment, Φ_{1r} , is obtained by folding the spectrum with the silicon displacement damage response as is described in Practice E722. The gain values, h_{FEO} before irradiation, and $h_{FE\Phi}$ after irradiation are measured, and the left side of Eq 1 is calculated. The following quantity can be defined.

$$\Delta \left(\frac{1}{h} \right) = \frac{1}{h_{FE\Phi}} - \frac{1}{h_{FEO}} \quad (2)$$

This is the change in reciprocal gain. A subscript of r is used to denote the reciprocal gain change in the reference calibration environment. A subscript of t is used to denote the reciprocal gain change in the test or unknown environment. This measurement and the known value of Φ_{1r} in the reference environment provide the calibration for the transistor, K_τ .

7.6 When the $\Delta (1/h)$ is measured in the unknown test environment, the Φ_{1t} can be found in the following manner. Take the ratio of equations (Eq 1) for the reference and test environments and rearrange the terms to yield Eq 3 (see Ref (3)).

$$\Phi_{1t} = \frac{\Delta \left(\frac{1}{h} \right)_t}{\Delta \left(\frac{1}{h} \right)_r} \Phi_{1r} = \frac{1}{K_\tau} \Delta \left(\frac{1}{h} \right)_t \quad (3)$$

7.7 The Φ_{1t} is the quantity needed as a sensor value in the spectrum determination procedure. The $\Delta (1/h)_t$ is the change in the reciprocal gain induced by the test environment. For neutron damage on 2N2222A transistors, K_τ is a constant for neutron fluences up to about 10^{15} n/cm^2 . The method described here provides a direct determination of Φ_{1t} .

8. Experimental Procedure

8.1 To ensure proper calibration of the sensor, follow the steps described in 8.1.1 – 8.1.9.