



Designation: E 1855 – 04^{ε1}

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 E 1855; 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 reappraisal. A superscript epsilon (ε) indicates an editorial change since the last revision or reappraisal.

^{ε1} NOTE—Editorial corrections were made in Equation 5 and throughout the document in April 2005.

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 equivalent displacement damage fluence monitors.

1.2 The neutron displacement damage is especially valuable as a 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 1015 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 *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 listed in 2.2 from Terminology E 170 through Test Method E 265 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.

2.2 *ASTM Standards:*²

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 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.

E 170 Terminology Relating to Radiation Measurements and Dosimetry

E 261 Practice for Determining Neutron Fluence Rate, Fluence, and Spectra Radioactivation Techniques

E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron

E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32

E 720 Guide for Selection and Use of Neutron-Activation Foils for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics

E 721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics

E 722 Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics

E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E706 (IIC)

E 854 Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Surveillance, E706 (IIIB)

E 944 Practice for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, (IIA)

E 1854 Practice for Ensuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts

E 2005 Guide for the Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron Fields

3. Terminology

3.1 *Symbols:*

Φ_1 = the silicon 1-MeV equivalent fluence (see Practice E 722).

$h_{FE} = i_c/i_b$ 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 the reference environment is derived from the known reference spectrum and is used to determine a measured Φ_{1t} in the test environment (1,2)³ by the transfer technique. The _r and _t refer to the reference and test environments respectively.

4.2 The measured Φ_{1t} 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 E 1854). Typically, 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 E 721). In particular, for silicon devices exposed in reactor neutron spectra, this effective energy range is between 0.01 and 10 MeV. A typical set of activation reactions which 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.

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

5.2 If fission foils are a part of the sensor set, the silicon sensor provides an important 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 easy and quick to read provided the proper steps are taken. They also can be used directly in arrays to map 1-MeV 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 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 E 722.

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 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 either during the calibration or test step, 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.

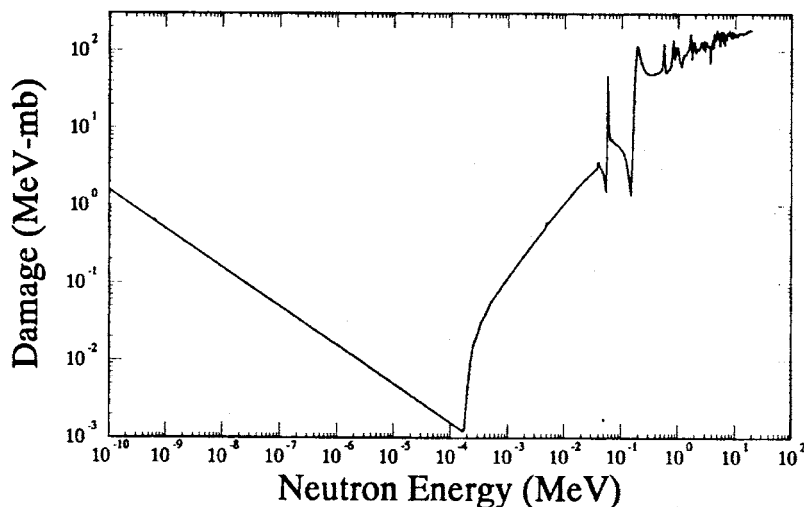


FIG. 1 Silicon Displacement Damage Response Function

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, where i_c is the collector current and i_b is the base current. The bias voltage is measured between the collector and the base (see Ref (5)).

6.4 A reference neutron source (see Guide E 2005) 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 the Fast Burst Reactors (FBRs) at Sandia National Laboratories, White Sands Missile Range, and Aberdeen Proving Ground also are recommended as reference benchmark fields.

6.5 If the transistors are exposed on a different run than the one used to expose foils for spectrum determination, a suitable monitor such as a nickel foil must be exposed along with the transistors during calibration to relate the magnitude of the neutron fluence during the spectrum determination exposure to that during the transistor calibration exposure (see Section 7). A photon-sensitive (and neutron insensitive) detector such as a CaF_2 thermoluminescent detector (TLD) shall be included in each test package to monitor the gamma-ray dose in case a correction must be made for the transistor damage from gamma-rays.

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 equivalent fluence, Φ_{1r} , at fixed collector current according to the Messenger-Spratt equation (7), if gamma rays do not contribute to the change of gain.

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

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_r 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 as long as the currents do not exceed the limits detailed in 8.1.2 and 8.1.3.

7.3 Since K_r differs for each transistor, each must be calibrated. When the technology of manufacture is such that the K_r 's within a batch are the same to within a few percentage

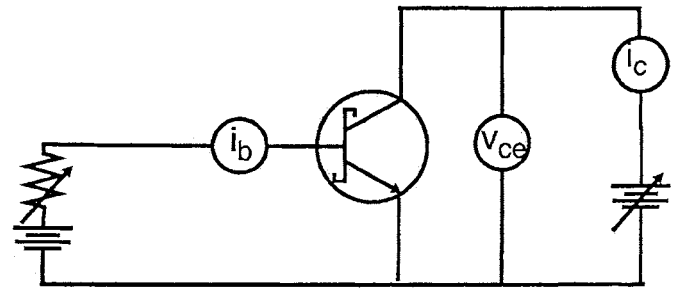


FIG. 2 Schematic for Transistor Read-Out

points, a calibration by batch may be satisfactory. A typical value for K_r 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 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 E 722. 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_r .

NOTE 1—As mentioned in 6.5, if the transistors are exposed on a different run than the run for measuring the spectrum, a monitor foil must be included with the transistors. This monitor foil should be the same as one of the sensor set so that a simple ratio of the monitor responses multiplied by the transistor response will provide the proper scaling between the runs. This procedure of using the ratio of activities to scale the fluences is valid because the same spectrum is used for both runs.

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)).

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

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_r is a constant for neutron fluences up to about 10^{15} n/cm^2 . The method described

here provides a direct determination of Φ_{1f} . Strictly speaking, if Φ_{1f} is the only quantity desired from the test when the transistor is irradiated, then a monitor is not needed. However, it is recommended that a monitor be included for possible scaling and for ensuring that the ratio of responses between the transistors and the monitor remain the same at characterized positions in the neutron field.

8. Experimental Procedure

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

8.1.1 *Step 1*—The 2N2222A transistors are inexpensive and can be purchased in large lots from electronic supply houses. Those purchased from readily available commercial sources have been found to be fairly uniform in electrical properties and come with initial gains between about 50 and 200. The first step is to measure, at 1 mA collector current, the initial gain values of all the transistors in the batch. Throw out all those with gain less than 100, and then remove the top and bottom 5 % fractions of the remaining set. Thus, if one begins with 100 transistors there may be two with gains below 100, and after removing 10 % of the remaining distribution, one might end up with about 88 transistors that can be calibrated. If the calibration environment is large enough to provide a uniform fluence to all the transistors on the same run, it is best to calibrate the whole batch together. The minimum number of transistors should be three.

8.1.2 The gain measurements may conveniently be made with a programmable semiconductor parameter analyzer, or with a specially designed circuit tester. The measurement details provided in 8.1.2.1-8.1.2.6 correspond to the steps on an HP 4145A programmable semiconductor parameter analyzer with an HP16058A Test Fixture. Any equivalent method for making the electrical measurement is acceptable as long as the currents do not exceed the limits detailed in 8.1.2 and 8.1.3. The manuals for other parameter analyzers can be used to see how this procedure should be adopted to other equipment.

8.1.2.1 *Setup*—Place the transistor in the test fixture. Note the assignment of leads to the transistor collector, base, and emitter.

8.1.2.2 *Channel Definition*—Use the channel definition screen to assign the variables, V_E/I_E , V_B/I_B , and V_C/I_C , to the nomenclature for the proper lead. The V stands for voltage, I for current, B for base, C for collector, and E for emitter.

8.1.2.3 *Source Setup*—Use the source setup screen to initialize the variable ranges for the measurements and the constraints or compliance rules for the measurements. I_B should be variable with 71 logarithmic steps from 100 pA to 1 mA. The V_B compliance voltage is 10 volts. V_{CE} is set as a fixed parameter of 10 V with a compliance current of 18 mA. I_C is assigned a compliance current of 18 mA.

NOTE 2—The upper bound placed on the base current range will never be reached given a nominal device gain of 100 and a maximum collector current of 1 mA. The nominal maximum base current seen during a measurement is ~ 0.01 mA. The base current range is set so that it does not prove to be a limiting factor for a properly operating 2N2222A transistor.

8.1.2.4 *Plot*—Set the display variables and ranges. Set the x-axis variable to I_C with a logarithmically spaced range from

1 μ A to 12 mA. Set the first y-axis variable to I_B with a logarithmic range from 100 pA to 15 mA. Set the second y-axis variable to h_{FE} with a linear range from 0 to 250. The second y-axis appears on the right-hand side of the plot.

8.1.2.5 *Measurement*—Have the analyzer make the measurements initialized in the setup and display the resulting plot. The transistor measurements are automatically made with a 3 ms pulse at each of the defined base current settings. The plot will be displayed with collector current along the bottom axis, base current along the left-hand side, and gain along the right-hand side. A marker (highlighted spot) will appear on the plot. The x and y values for this highlighted point will appear in a text screen above the plot. No measurements are made for settings that are outside the compliance conditions. Thus for collector currents above 18 mA, both curves drop to zero. The gain curve should be fairly flat except for very low base currents.

8.1.2.6 *Data Extraction*—Use the marker dial to move the pointer along the x-axis until the I_C value is 1 mA. A value for I_B and h_{FE} will be displayed on the top of the plot. These values can be verified by looking at the y-axis values for the two curves drawn on the plot. Record the h_{FE} gain value.

8.1.3 The measurement procedure detailed in 8.1.2.5 was designed to avoid large currents that would saturate the device or result in current-injection annealing of the radiation-induced damage to the test 2N2222A transistor. Collector currents larger than 1 mA should not be permitted except in a pulsed mode of operation. In pulsed mode, collector currents of up to 20 mA are permitted with pulse widths less than ~ 4 ms. Collector current measurements of 1 mA may be made in a steady state mode. The measurement procedure detailed in 8.1.2 had 71 logarithmically spaced steps with a maximum collector current of 18 mA. If a different pulsed readout method is used, the amount of time (number of steps multiplied by the pulse time) spent at collector currents greater than 1 mA should not significantly exceed that which results from the described procedure. At collector currents lower than 1 mA the gains are less reproducible and are more sensitive to temperature and gamma-ray background contributions. There are also surface and emitter losses. At higher collector currents, there can be emitter crowding, nonlinearities and heating effects. A standardized sequence and duration of measurement is necessary because of variations of the charge state of traps within the devices, particularly after exposure to ionizing radiation (from sources such as the gamma-ray background).

NOTE 3—Avoid handling the transistors with fingers just before reading, because the warmed transistors will exhibit a higher gain. When reading the gains, intersperse the control transistors with the test transistors and try to maintain uniform temperature throughout the readout process. It is good practice to have all transistors in the same temperature environment for approximately 5 minutes before the device readout begins.

8.1.4 *Step 2*—Separate out at least three transistors to be used as controls for correcting the gain measurements to account for differences in the temperature of the transistors when they are read after each exposure and anneal step of the transistors. The temperature dependence of the gain is expected to be different for unirradiated and irradiated transistors. Therefore the transistors that are to be used to compare the