



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

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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 1 Mev(Si) equivalent displacement damage fluence monitors.

1.2 The neutron displacement in silicon can serve 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 to 1×10^{14} n/cm² and should be useful up to 1×10^{15} n/cm². This test method details the acquisition and use of 1 Mev(Si) equivalent fluence information for the partial determination of the neutron spectra by using 2N2222A transistors.

1.3 This sensor yields a direct measurement of the silicon 1 Mev equivalent 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 a measured reference neutron environment. The Φ_{1r} in the

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.

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. 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 combined with 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 test spectrum must be known in order to use a measured device response to predict the device performance in an operational environment (E1854). Typically, neutron spectra are determined by use of a set of sensors with response functions sensitive over the neutron energy region to which the device under test (DUT) responds (E721). 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.

5.2 When dosimeters with a significant response in the 10 keV to 2 MeV energy region, such as fission foils, are unavailable, silicon transistors may provide a dosimeter with the needed response to define the spectrum in this critical energy range. When fission foils are part of the sensor set, the silicon sensor provides confirmation of the spectral shape in this energy region.

5.3 Silicon bipolar transistors, such as type 2N2222A, are inexpensive, smaller than fission foils contained in a boron ball, and 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 displacement damage fluence. The proper set of steps to take in reading the transistor-gain degradation is described in this test method.

5.4 The energy-dependence of the displacement damage function for silicon is found in E722. The major portion of the response for the silicon transistors will generally be above 100 keV.

6. Apparatus

6.1 The 2N2222A silicon bipolar transistor has a demonstrated response in agreement with calculated Φ_1 values in widely varied environments (5). It is recommended that three or more transistors be calibrated together and used at each location to be characterized. At least three transistors should be used as control devices. 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.

6.3 An electronic system is required to maintain appropriate transistor bias and currents and to read the currents for the gain measurements. 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 (6)).

6.4 A reference neutron source (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 (7) are recommended for use as primary standards, and a well characterized fast burst reactor, 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, shall be exposed along with the transistors during exposures. A photon-sensitive detector such as a CaF₂ thermoluminescence detector (TLD) shall be included in each test package to monitor the gamma ray dose. 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 CaF₂:Mn TLD for the neutron response.

NOTE 1—Ionizing dose is produced by photon irradiation in bulk silicon and SiO₂. 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 displacement damage fluence, Φ_1 , at fixed collector current according to the Messenger-Spratt equation (8), 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 quantity measured at the 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).

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

7.2 A basic schematic circuit used by semiconductor analyzers for measuring $h_{FE} = i_c/i_b$ is shown in Fig. 1. A semiconductor parameter analyzer may be used to determine h_{FE} . Any equivalent method for making the electrical measurement is acceptable. 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_t differs for each transistor, each must be calibrated; see paragraph 8.1.1. A typical value for K_t is about 1.5×10^{-15} cm²/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 displacement damage 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.

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

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} provide the calibration for the transistor, K_t .

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(3).

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

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 reciprocal gain induced by the test environment. For neutron damage on 2N2222A transistors, K_t is a constant for neutron

fluences up to about 1×10^{15} n/cm². The method described here provides a direct determination of Φ_{1t} .

7.8 The 2N2222A may be used as a 1 MeV-(Si) displacement monitor. In this use, Eq 3 gives the desired quantity directly, independent of the neutron spectrum. The gamma-ray corrections must be made. This may be useful, for example, to measure the 1 Mev(Si) displacement damage at several locations inside a massive test item without a full spectral measurement at each point.

8. Experimental Procedure

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

8.1.1 *Step 1*—Measure, at 1 mA, I_c , the initial gain values of all the 2N2222A transistors in the batch. Throw out all those with gain less than 100 and then remove the top and bottom 5 % of the remaining set. 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. Three is the minimum number of transistors.

8.1.2 The gain measurements may conveniently be made with a programmable semiconductor parameter analyzer, or with a specially designed circuit tester.

8.1.2.1 *Setup*— I_B should be variable from 100 pA to 1 mA. The V_B compliance voltage is 10 V. V_{CE} is 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.

8.1.2.2 *Measurement*—Vary resistance high to low till I_c is 1 mA. Measure I_B , $h_{FE} = I_c/I_B$. For pulsed measurements the transistor measurements are made with a 3 ms pulse at each of the defined base current settings.

8.1.2.3 *Data Recording*—Record all I_C and I_B measurements. Use the I_C value at 1 mA to calculate I_c/I_B .

8.1.3 The measurement procedure 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. The measurement procedure detailed in 8.1.2 had a maximum collector current of 18 mA. If a different pulsed readout method is used, the amount of time spent at collector currents greater than 1 mA should not significantly exceed that which results from the described procedure. 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). Collector current measurements of 1 mA and down to 0.1 mA may be made in a steady state mode. At collector current

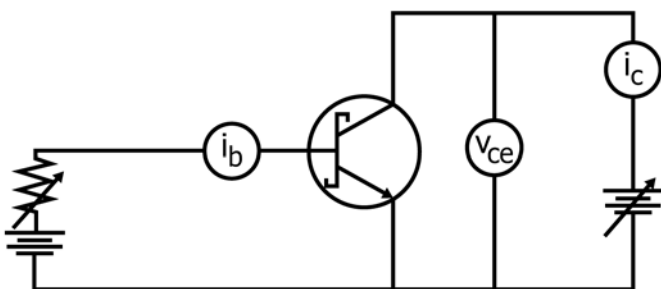


FIG. 1 Schematic for Transistor Read-Out