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Designation: ~~E1855 – 10~~ E1855 – 15

Standard Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors[1]

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,~~spectra and as ~~silicon 1-MeV(Si)~~1 Mev(Si) equivalent displacement damage fluence monitors.

1.2 The neutron displacement ~~damage is especially valuable~~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/cm^2 ~~and~~to 1×10^{14} n/cm^2 and should be useful up to 1×10^{15} n/cm^2. This test method details the ~~steps for the~~ acquisition and use of ~~silicon 1-MeV~~1 Mev(Si) equivalent fluence information ~~(in a manner similar to the use of activation foil data) for the determination of neutron spectra.~~for the partial determination of the neutron spectra by using 2N2222A transistors.

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

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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.

ASTM E1855-15
https://standards.iteh.ai/catalog/standards/sist/a8e9edee-1d73-42bf-968e-7290faefbd2c/astm-e1855-15

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 CaF_2(Mn) Thermoluminescence Dosimeters in Mixed Neutron-Photon Environments

[1] This test method is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applicationsand 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.

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3. Terminology

3.1 *Symbols:*

Φ_1 = the silicon ~~1-MeV~~ 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~~a 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 subscripts *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~~ 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 ~~spectrum in a test (simulation) environment~~ test spectrum 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~~ with response functions ~~that are~~ sensitive over the neutron energy region to which the device under test (DUT) responds ~~(see Guide~~ (E721). ~~In particular, for~~ 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 ^{235}U, ^{237}Np, or ^{239}Pu, 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~~ 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 ~~spectrum shape.~~spectral shape in this energy region.

5.3 ~~Bipolar~~ Silicon 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~~ 1 Mev(Si) equivalent displacement damage fluence. The proper set of steps to take in reading the transistor-gain degradation is ~~the primary subject of~~ described in this test method.

5.4 ~~Fig. 1 shows the~~ The energy-dependence of the displacement damage function for ~~silicon. As can be~~silicon is found in E722~~seen from the figure, the~~ . 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.~~

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6. Apparatus

6.1 ~~A transistor with~~ The 2N2222A silicon bipolar transistor has a demonstrated response in agreement with calculated Φ_1 values in widely varied environments ~~is~~(**5**). ~~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~~transistors should be used as ~~temperature correction devices (control devices) during readout.~~ control devices. The control transistors should be exposed one time to a calibration exposure of about 1.0 × 10^{13} n/cm^2 ~~1-MeV(Si)~~ 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 ±3.0°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. ~~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

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

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 (**56**)).

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 (**67**) are recommended for use as primary standards, and a well characterized Fast Burst Reactor (FBR), 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 shouldfoil, shall be exposed along with the transistors during calibration to relate to the magnitude of the neutron fluence. exposures. A photon-sensitive detector such as a CaF_2 thermoluminescentthermolumenescence 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. 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 CaF_2: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 1 Mev(Si) equivalent displacement damage fluence, Φ_1, at fixed collector current according to the Messenger-Spratt equation (**78**), if gamma rays do not contribute to the change of gain.

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

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. 21. A semiconductor parameter analyzer may be used to determine h_{FE}. Any equivalent method for making the electrical measurement is acceptable but the 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_τ differs for each transistor, each must be calibrated. When thecalibrated; see paragraph 8.1.1technology of manufacture is such that 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 × 101.5 × 10^{-15-15} cm^2/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 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.

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

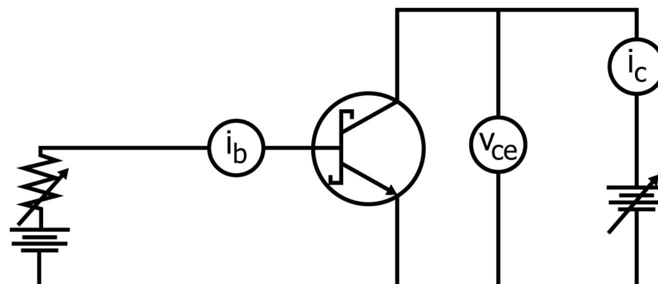

FIG. 21 Schematic for Transistor Read-Out

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**))~~.~~.~~

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

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 1×10^{15} n/cm^2. 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 ~~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~~Measure, at 1 mA, ~~*collector*~~I_c, ~~current,~~ the initial gain values of all the 2N2222A transistors in the batch. Throw out all those with gain less than ~~100,~~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. ~~The~~ Three is the minimum number of ~~transistors should be three.~~transistors.

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.~~

8.1.2.1 ~~*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 at least 71 logarithmic steps~~ from 100 pA to 1 mA. The V_B compliance voltage is 10 ~~volts.~~V. 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 µA 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.~~

8.1.2.2 *Measurement*—~~Make the measurements initialized in the~~Vary resistance high to low till ~~*setup*~~I_c ~~and display the resulting~~is 1 mA. Measure ~~*plot.*~~I_B,h_{FE} ~~The~~= I_c/I_B. For pulsed measurements 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.~~

8.1.2.3 *Data* ~~*Extraction*—~~*Recording*—~~Move the pointer along the~~ Record all ~~*x-axis until the*~~ I_C ~~value is 1 mA. A value for I_B and h~~I_B~~$_{FE}$ will be displayed on the top of the plot. These values can be verified by looking at the~~ measurements. Use the ~~*y*~~I_C~~-axis values for the two curves drawn on the plot. Record the~~ value at 1 mA to calculate ~~*h*~~I_C/I_B~~.$_{FE}$ 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

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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).~~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 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.

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 min before the device readout begins.

8.1.4 *Step 2*—~~Separate out at least~~ Isolate 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~~un-irradiated and irradiated ~~transistors. Therefore the transistors that are to be used to correct the measured gains for the temperature at readout (the control transistors)~~transistor. Therefore, the control transistors shall be exposed to a neutron fluence of ~10^{13} n/cm^2 and then annealed at 180°C for 24 h followed by ambient air cooling before ~~they are used as controls. From then on the controls should not be~~ use. Controls shall not be further exposed or annealed. For example, after the calibration run, the control transistors are read for gain along with the exposed transistors. The temperature correction factor R_c, is computed using:

$$R_c = \frac{1}{n}\sum_{i=1}^{n}\frac{R_i}{C_i} \tag{4}$$

where:

n = number of control transistors,
R_i = transistor gain of the present readout for the ith control transistor, and
C_i = transistor gain of the ith control transistor determined in 8.1.1.

8.1.5 *Step 3*—Expose the sensor transistors uniformly in the reference neutron environment, unbiased and with the leads shorted. ~~It~~Appendix X1 ~~is important~~ shows how the nonlinear propagation of gain measurement error into the implied 1–MeV(Si) fluence can result in significantly larger fluence uncertainties. For smaller exposed fluences, the multiplication factor in the gain-to-fluence uncertainty is much larger. For a nominal irradiation where the gain is degraded by 30 %, a 1 % uncertainty in the gain measurements can, in a worst-case anti-correlated scenario addressed in Appendix X1~~that the irradiation~~ , result in a 5 % uncertainty in the implied neutron fluence. Since use of the silicon gain degradation as a dosimeter requires that the uncertainty in the implied neutron fluence be small, the irradiation should be sufficient to degrade the gain by ~~about 30 % or more.~~ ≃30 % or more. An upper limit on the neutron fluence is motivated by the larger fractional measurement uncertainty when the transistor gain is degraded to levels less than ~5. For a fast neutron spectrum and using a representative damage constant of $K_\tau = 1.5 \times 10^{-15}$ cm^2~~this means 5 × 10~~/neutron and an initial gain of 90, this desired 30 % change in gain and consideration of the maximum gain degradation means that ~5×10^{12} ~~n/cm~~1–MeV(Si)-eqv.-n/cm^2 ≤ Φ_1 ≤ ~~1 × 10~~≃1×10^{14} ~~n/cm~~1 Mev(Si)-eqv.-n/cm^2. ~~See Appendix X1 for an explanation of the choice of the lower limit.~~ Include monitor foils ~~such as~~ nickel or ~~sulfur,~~sulfur and include TLDs in the irradiation package.

8.1.6 *Step 4*—In order to remove the variations associated with ambient temperature annealing during and after the irradiation, an annealing step at 80°C for two hours shall be performed before readout. This will only be effective in ensuring reproducible results if the environmental conditions during irradiation and subsequent handling do not include exposure at temperatures above 60°C. An additional precaution is to standardize the delay time between irradiation and readout. Annealing at 80°C for ~~two hours~~2 h removes no more than 20 % of the displacement ~~damage.~~damage **(9)**. Under this condition, fading (further annealing) has not been observed. Do not anneal the control ~~transistors once they have been prepared as described in~~ transistors.~~8.1.4.~~

NOTE 4—The importance of limiting the exposure of the device to high currents was discussed in 8.1.3. In addition to the annealing by high current charge injection, there are other high current-related effects that can reverse the annealing of some types of silicon defects. There is a ~~bistable~~bi-stable silicon defect (**~~8~~10,~~9~~11**) that, under high current charge injection, can reverse the effects of the stabilizing anneal step discussed in 8.1.6~~, that is, decrease~~. This results in a decrease in the gain. After ~~such~~ a high current exposure, the transistor may again be ~~subject~~subjected to a time-dependent annealing under ambient temperature/time conditions.

8.1.7 *Step 5*—Measure the gains of the controls and sensors under standardized conditions. The environmental temperature during this measurement shall be within 10°C of the pre-irradiation measurement temperature.

8.1.8 *Step 6*—Apply a correction to the post-irradiation gain values for the effect of the difference in temperature between the initial characterization and the present reading. This may be done either by means of a measured temperature coefficient of irradiated transistors that have been annealed (see 8.1.4), or by multiplying the observed gain values by the ratio of the average

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of the ~~values of the controls,~~ control values as measured when the sensors were first being read, to their average gain values measured at the same time as the post-irradiation ~~measurement of the sensors as described in~~ measurement.~~8.1.4.~~

8.1.9 *Step 7*—Use the monitor foil activity as a normalizing factor and the reference environment spectrum to determine Φ_{1r}, which was experienced during the sensor calibration. The normalization is accomplished by multiplying Φ_1, determined when the spectrum was measured by the ratio of the monitor foil activities in the respective spectrum and calibration exposure. Then calculate K_τ from Eq 1 for each transistor.

8.2 *Determination of the Measured Φ_{1t} in the Test Environment:*

8.2.1 *Step 8*—After the calibration readout and before exposure in the test environment, the transistors shall be given a "hard anneal" to further stabilize and reset the gains before the next exposure. The recommended annealing is 180°C for 24 h. This annealing will ~~heal~~recover about 70 % of the damage caused by the latest irradiation (see Ref **(9)**) so that the sensor can be used in more than one test environment.

8.2.2 *Step 9*—The initial gain, h_{FEO}, to be used in this second application of Messenger's Eq 1 is the gain after the "hard anneal" described in 8.2.1, because it is the new gain change induced by the test environment that we want to determine. Measure the gain of each transistor after the above hard anneal. Make certain ~~that~~ the transistors have ~~had the opportunity to cool down to~~ cooled to ambient temperature before reading these gains. Apply the temperature correction described in 8.1.4 by using the control transistor gain ratios obtained in Step 1 and Step 9 (the latter obtained by reading the controls again with the test transistors).

8.2.3 *Step 10*—Expose the calibrated transistor sensors in the test environment along with monitor foils. Steps 3 through 5 must be repeated.

NOTE 5—If the same transistor is exposed three times or more with hard anneals between each irradiation, a correction for the gain recovery during hard anneals for earlier groups must be ~~made (see Ref~~ made.~~(4)).~~

8.2.4 *Step 11*—Apply the temperature correction to the exposed transistors in accordance with 8.1.4.

8.2.5 *Step 12*—Use the new gain values obtained in 8.2.2 ~~(the new values of~~ with h_{FEO}~~) and~~ those obtained in 8.2.4 to calculate the change in the reciprocal of the gains, Δ (1/*h*), in Eq 3. Multiply $\Delta (1/h)_\tau$ by $1/K_\tau$ to determine Φ_{1t} for each transistor. Average the Φ_{1t} values for transistors in the same location to determine the most likely value of Φ_{1t}.

8.2.6 *Step 13*—Check the ratio of the monitor foil and TLD readings to determine whether a correction for gamma ray damage is necessary. If so, apply corrections as discussed in 8.3 – 8.3.3.

8.3 *Potential Gamma Ray Effects:*

8.3.1 Gamma rays will always be present in reactor-produced neutron environments. Under normal circumstances the atomic displacements and the displacements generated by Compton-scattered electrons will contribute a negligibly small percent of the damage generated by neutrons. However, ionizing dose to the oxides in the transistor can trap charge that affects the electric fields in the transistor and change the device gain. In some environments, the gamma ray-to-neutron fluence ratio can be so large that corrections need to be made to the gain measurement.~~ This standard only addresses the Δ (1/h) from neutron displacements.~~

NOTE 6—Some activation foils may also be affected by gamma rays if the flux and photon energy are high enough to generate (γ,γ') (γ,n), (γ,np) and (γ,p) reactions that lead to the daughter isotopes being counted as neutron reactions. The thresholds for (γ,p) and (γ,np) reactions tend to be above 7 MeV for typical activation foil materials.

8.3.2 To monitor for ~~gamma ray~~ gamma-ray contributions, TLDs or an ionizing dose sensor shall be included with all sensor sets. For this discussion, define the symbol γ, when not used in an expression such as (n,γ), to mean the ~~gamma ray~~ gamma-ray ionizing dose to silicon. Use the 1 ~~MeV(Si)~~ Mev(Si) equivalent displacement damage fluence from the reference spectrum and that derived from Eq 3 for the test spectrum to calculate Φ_1/γ ratios for the two environments. The γ values are obtained from the TLD readings for the two cases. If either of these ratios is less than 10^{11} ~~neutrons/[cm~~neutrons/cm^2~~ × Gy(Si)]~~/Gy(Si) then a correction may have to be applied to the Δ (1/*h*) for gamma ray damage. This means that the $\Delta (1/h)_\gamma$ from the gamma ray induced damage must be subtracted from the total measured $\Delta (1/h)_T$ to yield Δ (1/*h*) from the neutrons to be used in Eq 1. An approximate value of $\Delta (1/h)_\gamma$ can be determined by exposing the transistors to a ^{60}Co source along with TLD monitors. In the γ sensitivity calibration, the transistors shall also be annealed at ~~80°C for 2 h~~ 80 °C for 2 h before they are read. The measured $\Delta (1/h)_\gamma$ is then scaled by the ratio of the TLD doses measured in the test and ^{60}Co environments to yield the $\Delta (1/h)_\gamma$ in the test environment. This should be done for each transistor. For the purpose of making estimates, the gamma ray sensitivity for some 2N2222A transistors has been measured to be approximately:

$$K_\gamma = \frac{\Delta\left(\frac{1}{h}\right)_\gamma}{D_\gamma\,(TLD)} \approx 1.5 \times 10^{-5}\ Gy^{-1} \quad (5)$$

This value of K_γ may not be valid if the test gamma-ray ~~ray~~ spectrum is very different from that of the ^{60}Co gamma ray source. It is best to choose a reference environment for which the gamma ray correction would be negligible.

8.3.3 *^{60}Co Tests*—If necessary, expose transistors to ^{60}Co irradiation to a level comparable to that measured by the TLDs in the test environment and establish the effect on Δ (1/*h*). Subtract this contribution from the Δ (1/*h*) measured in the test environment.

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