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Standard Guide for Neutron Irradiation of Unbiased Electronic Components[1]

This standard is issued under the fixed designation F1190; 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 strictly applies only to the exposure of unbiased silicon (Si) or gallium arsenide (GaAs) semiconductor components (integrated circuits, transistors, and diodes) to neutron radiation from a nuclear reactor source to determine the permanent damage in the components. Validated 1-MeV displacement damage functions codified in National Standards are not currently available for other semiconductor materials.

1.2 Elements of this guide, with the deviations noted, may also be applicable to the exposure of semiconductors comprised of other materials except that validated 1-MeV displacement damage functions codified in National standards are not currently available.

1.3 Only the conditions of exposure are addressed in this guide. The effects of radiation on the test sample should be determined using appropriate electrical test methods.

1.4 This guide addresses those issues and concerns pertaining to irradiations with reactor spectrum neutrons.

1.5 System and subsystem exposures and test methods are not included in this guide.

1.6 This guide is applicable to irradiations conducted with the reactor operating in either the pulsed or steady-state mode. The range of interest for neutron fluence in displacement damage semiconductor testing range from approximately 10^9 to 10^{16} 1-MeV n/cm^2.

1.7 This guide does not address neutron-induced single or multiple neutron event effects or transient annealing.

1.8 This guide provides an alternative to Test Method 1017.3, Neutron Displacement Testing, a component of MIL-STD-883 and MIL-STD-750. The Department of Defense has restricted use of these MIL-STDs to programs existing in 1995 and earlier.

1.9 *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 limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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

E668 Practice for Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices

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

E1249 Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources

E1250 Test Method for Application of Ionization Chambers to Assess the Low Energy Gamma Component of Cobalt-60 Irradiators Used in Radiation-Hardness Testing of Silicon Electronic Devices

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

E2450 Practice for Application of CaF$_2$(Mn) Thermoluminescence Dosimeters in Mixed Neutron-Photon Environments

F980 Guide for Measurement of Rapid Annealing of Neutron-Induced Displacement Damage in Silicon Semiconductor Devices

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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 on Nuclear and Space Radiation Effects.

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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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2.2 *Other Documents:*

2.2.1 The Department of Defense publishes every few years a compendium of nuclear reactor facilities that may be suitable for neutron irradiation of electronic components:

DASIAC SR-94-009, April 1996, Guide to Nuclear Weapons Effects Simulation Facilities and Techniques[3]

2.3 *The Office of the Federal Register, National Archives and Records Administration publishes several documents that delineate the regulatory requirements for handling and transporting radioactive semiconductor components:*

Code of Federal Regulations: Title 10 (Energy), Part 20, Standards for Protection Against Radiation[4]

Code of Federal Regulations: Title 10 (Energy), Part 30, Rules of General Applicability to Domestic Licensing of Byproduct Material[4]

Code of Federal Regulations: Title 49 (Transportation), Parts 100 to 177[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *1-MeV equivalent neutron fluence* $\Phi_{eq,\ 1\ MeV,\ Si}$ —this expression is used by the radiation-hardness testing community to characterize an incident energy-fluence spectrum, Φ(E), in terms of monoenergetic neutrons at a specific energy, E_{ref} = 1 MeV, required to produce the same displacement damage in a specific irradiated material, denoted by the subscript as "matl" (see Practice E722 for details).

3.1.1.1 *Discussion*—Historically, the material has been assumed to be silicon (Si). The emergence of gallium arsenide (GaAs) as a significant alternate semiconductor material, whose radiation damage effects mechanisms differ substantially from Si based devices, requires that future use of the 1-MeV equivalent fluence expression include the explicit specification of the irradiation semiconductor material.

3.1.2 *equivalent monoenergetic neutron fluence* ($\Phi_{eq,Eref,\ matl}$)—an equivalent monoenergetic neutron fluence that characterizes an incident energy-fluence spectrum, Φ(E), in terms of the fluence of monoenergetic neutrons at a specific energy, E_{ref}, required to produce the same displacement damage in a specified irradiated material, matl (see Practice E722 for details).

3.1.2.1 *Discussion*—The appropriate expressions for commonly used 1-MeV equivalent fluence are $\Phi_{eq,\ 1\ MeV,\ Si}$ for silicon semiconductor devices and $\Phi_{eq,\ 1\ MeV,\ GaAs}$ for gallium arsenide based devices. See Practice E722 for a more thorough treatment of the meaning and significant limitations imposed on the use of these expressions.

3.1.3 *silicon damage equivalent (SDE)*—expression synonymous with "1-MeV(Si) equivalent fluence in silicon."

4. Summary of Guide

4.1 Evaluation of neutron radiation-induced damage in semiconductor components and circuits requires that the following steps be taken:

4.1.1 Select a suitable reactor facility where the radiation environment and exposure geometry desired are both available and currently characterized (within the last 15 months). Practice E1854 contains detailed guidance to assist the user in selecting a reactor facility that is certified to be adequately calibrated.

4.1.2 Prepare test plan and fixtures,

4.1.3 Conduct pre-irradiation electrical test of the test sample,

4.1.4 Expose test sample and dosimeters,

4.1.5 Retrieve irradiated test sample,

4.1.6 Read dosimeters,

4.1.7 Conduct post-irradiation electrical tests, and

4.1.8 Repeat 4.1.4 through 4.1.7 until the desired cumulative fluence is achieved or until degradation of the test device will not allow any further useful data to be taken.

4.2 Operations addressed in this guide are only those relating to reactor facility selection, irradiation procedure and fixture development, positioning and exposure of the test sample, and shipment of the irradiated samples back to the parent facility. Dosimetry methods are covered in existing ASTM standards referenced in Section 2, and many pre- and post-exposure electrical measurement procedures are contained in the literature. Dosimetry is usually supplied by the reactor facility, see Practice E1854.

5. Significance and Use

5.1 Semiconductor devices can be permanently damaged by reactor spectrum neutrons (**1, 2**)[5]. The effect of such damage on the performance of an electronic component can be determined by measuring the component's electrical characteristics before and after exposure to fast neutrons in the neutron fluence range of interest. The resulting data can be utilized in the design of electronic circuits that are tolerant of the degradation exhibited by that component.

5.2 This guide provides a method by which the exposure of silicon and gallium arsenide semiconductor devices to neutron irradiation may be performed in a manner that is repeatable and which will allow comparison to be made of data taken at different facilities.

5.3 For semiconductors other than silicon and gallium arsenide, applicable validated 1-MeV damage functions are not available in codified National standards. In the absence of a validated 1-MeV damage function, the non-ionizing energy loss (NIEL) or the displacement kerma, as a function incident neutron energy, normalized to the response in the 1 MeV energy region, may be used as an approximation. See Practice E722 for a description of the method used to determine the damage functions in Si and GaAs (**3**).

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[3] Available from Defense Special Weapons Agency, Washington, DC 20305-1000.

[4] Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

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

6. Interferences

6.1 *Gamma Effects:*

6.1.1 All nuclear reactors produce gamma radiation coincident with the production of neutrons. Prompt gamma rays are produced directly in the fission process, from neutron transmutation reactions with reactor support materials and test objects. Delayed gamma rays are emitted by fission products and activated materials. Furthermore, these gamma rays can produce secondary gamma rays and fluorescence photons in reactor fuel, moderator, and surrounding materials. Since degradation in piece part performance may be produced by gamma rays as well as neutrons, and because of the softer photon spectra dose enhancement may be a problem. If a separation of neutron (n) and gamma ray (γ) degradation is desired, either the n/γ ratio must be increased to the point at which gamma effects are negligible or the test sample degradation must first be characterized in a "pure" gamma ray environment and one must have a basis for believing that the damage mode of concern does not exhibit any synergy between the neutron and gamma response. The use of such data from a gamma ray exposure to separate neutron and gamma effects obtained during a neutron exposure may be a complex task. If this approach is taken, Guide F1892 should be used as a reference. Guides E1249 and E1250 should be used to address dose enhancement issues.

6.1.2 TRIGA-type reactors (Training Research and Isotope production reactor manufactured by General Atomics) deliver gamma dose during neutron irradiations that can vary considerably depending on the immediately preceding operating history of the reactor. A TRIGA-type reactor that has been operating at a high power level for an extended period prior to the semiconductor component neutron irradiation will contain a larger fission product inventory that will contribute significantly higher gamma dose than a reactor that has had no recent high level operations. The experimenter must determine the maximum gamma dose his experiment can tolerate, and advise the facility operator to provide sufficient shielding to meet this limit.

6.2 *Temperature Effects*—Annealing of neutron damage is enhanced at elevated temperatures. Elevated temperatures may occur during irradiation, transportation, storage, or electrical characterization of the test devices.

6.3 *Dosimetry Errors*—Neutron fluence is typically reported in terms of an equivalent 1-MeV monoenergetic neutron fluence in the specified irradiated material ($\Phi_{\mathrm{eq,\,1\,MeV,\,Si}}$ or $\Phi_{\mathrm{eq,\,1\,MeV,\,GaAs}}$) in units of neutrons per square centimeter. ASTM guidelines and standards exist for calculating this value from measured reactor characteristics. However, reactor facilities may not routinely re-measure the neutron spectrum, (using Guide E720 and Method E721) at the test sample exposure sites. A currently valid determination of the neutron spectrum is needed to provide the essential data to accurately ascertain the equivalent 1-MeV monoenergetic neutron fluence in the specified irradiated material. Lack of this critical data can result in substantial error. Therefore, the experimenter must request a current valid determination of the 1-MeV equivalent fluence in silicon or GaAs, as needed, from the reactor facility operator. This may require a re-characterization of the reactor test facility, or the particular test configuration. Practice E1854 discusses the roles of the facility, dosimetrist, and user.

6.4 *Recoil Ionization Effects*—Ionization effects from neutron-induced recoils of the lattice atoms within a semiconductor device may be significant for some device types at some reactor configurations, although under normal conditions, ionization due to the gamma radiation from the source will be much greater than the ionization from neutron-induced recoils.

6.5 *Test Configuration Effects*—Extraneous materials in the vicinity of the test specimens can modify the radiation environment at the test sample location. Both the neutron spectrum and the gamma field can be altered by the presence of such material even if these materials are not directly interposed between the reactor core and the test devices.

6.6 *Thermal Neutron Effects*—Fast Burst Reactor (FBR) neutron spectra have a small thermal neutron component; however, TRIGA reactors inherently produce a very large thermal neutron flux from the water moderation of the fission neutrons. Neutrons interact with the materials of the devices being irradiated causing them to become radioactive. Thermal neutrons generally induce higher levels of radioactivity. As a consequence, parts irradiated to moderate or high fluence levels at TRIGA reactors should not be handled or measured soon after exposure. It is therefore common practice at TRIGA reactors to shield test parts from the thermal neutrons with borated polyethylene or cadmium shields. Cadmium capture of thermal neutrons produces more gamma rays than boron capture, thus producing a lower n/γ ratio when such a shield is used. In addition, whereas cadmium has a strong capture cross section for neutrons with incident energies less than 0.3 eV, boron-10 has a significant (n,α) reaction with a 1/E energy fall-off that extends into the keV energy region. For these reasons, borated polyethylene shields are preferred. While most facilities providing neutron irradiation for semiconductor parts will automatically provide the thermal neutron shields, it is the experimenter's responsibility to verify that use of such a shield is considered during the irradiation.

7. Procedure

7.1 *Reactor Facility Selection :*

7.1.1 *Reactor Operating Modes and Fluence Levels*—Two types of reactors are generally used for evaluating the displacement effects of neutrons on electronic components. These reactors, the FBR and the TRIGA types, can be operated in either a pulsed or a steady-state mode. The minimum pulse width for the FBR is approximately 50 µs and the TRIGA type has a nominal pulse width >10 ms. No rate dependence of permanent displacement damage has been observed at these facilities. In the single-pulse mode, the FBR typically has a maximum fluence ($\Phi_{\mathrm{eq,\,1\,MeV,\,Si}}$) up to 8×10^{13} n/cm^2 outside the core and 6×10^{14} n/cm^2 inside the core. TRIGA-type reactors have a maximum single pulse fluence that varies with the reactor and the exposure position within the core, but ranges from 5×10^{13} to 6×10^{15} n/cm^2. The volumes (in-core for a TRIGA and in leakage mode for a FBR) available for semiconductor components for most FBR reactors and TRIGA